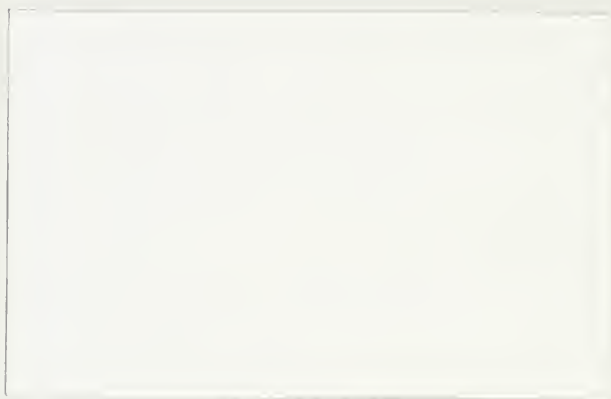


**IMPACT OF LIVESTOCK MANURE AND  
FERTILIZER APPLICATION ON  
NITRATE CONTAMINATION OF GROUNDWATER  
FINAL REPORT**

**RAC Project No. 488G**

**MINISTRY OF ENVIRONMENT AND ENERGY**



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## Executive Summary

This study examined the fate of nitrogen (N), as a function of N source ( $\text{NH}_4\text{NO}_3$ ), liquid dairy cattle manure (LCM) and solid beef manure (SBM), N application rate (high, medium and low) and N application time (fall and spring), once it is applied and incorporated into a soil used to grow corn. Agricultural specialization has resulted in larger livestock operations operating on smaller landbases in which much of the feed is imported to the farm. These large operations produce quantities of manure nitrogen in excess of that required by the associated cropped land. Disposal costs are high which results in excessive rates of manure being applied to the land. If disposal is the objective, little concern may be given to the effect of time, rate or method of manure application to the land.

This study was carried out at the Ontario Ministry of Agriculture and Food's Elora Research Station, Elora, Ontario between 1991 and 1994. Corn stover and grain yields and N concentrations were measured each year. Soil solution concentrations of nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ) were monitored each week during the growing season using solution samplers installed below the root zone (0.80 m depth). Amounts of soil mineral N, extractable N and extractable Carbon (C) were monitored at various times by taking soil samples at various depths. A detailed study of denitrification was undertaken in the summer of 1993. In addition, a detailed water balance in conjunction with a conservative tracer ( $\text{Cl}^-$ ) were used to characterize the chemical leaching process at this site.

Corn response to N source, N application rate and N application time was fairly consistent throughout the experiment. Overall, there were consistent differences between N rates in the order of high > medium > low with respect to N concentrations, grain yields and stover yields. Also, there were consistent differences between N application times in the order of spring > fall. Response to N source was somewhat varied. Control plot yields were not different from N source treated yields in 1991 which was attributed to residual N from the previous continuous corn system. The  $\text{NH}_4\text{NO}_3$  and LCM treated plots had larger yields than the SBM treated plots in 1991 but the

reverse was true in 1992. This was attributed to immobilization of N in the SBM treated plots in 1991 due to large amounts of added C and to leaching of plant available  $\text{NO}_3^-$  in the LCM and  $\text{NH}_4\text{NO}_3$  treated plots during the wet summer of 1992. No differences were observed during 1993 with respect to N source.

The  $\text{Cl}^-$  leaching experiments indicated that little downwards movement occurs during a normal (1991, 1993) growing season (May through September) when evapotranspiration is equal to or slightly greater than precipitation. Chemical movement during this time is an up and down one in response to evapotranspiration and precipitation which causes dispersion and a decrease of peak concentrations. However, during a very wet growing season (1992) or the period of maximum leaching (November through April),  $\text{Cl}^-$  was observed to leach downwards in a 'pulse' fashion. It was estimated that any mobile chemical ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ ) can be completely leached from the 0 - 80 cm depth during the period of maximum leaching. It was emphasized that the amounts of mobile chemicals, remaining in the soil profile, should be minimized after harvest.

The water flux averaged concentration of  $\text{NO}_3^-$  - N in the control (0 kg N  $\text{ha}^{-1}$  added) plots over the duration of the experiment was 6.4 mg N  $\text{L}^{-1}$ . This is only slightly below the drinking water quality standard of 10 mg N  $\text{L}^{-1}$ . All treatments resulted in an increase in the amount of  $\text{NO}_3^-$  - N in the leaching water. Except for the low rate of application of SBM, all treatments and rates resulted in  $\text{NO}_3^-$  - N concentrations that exceeded drinking water standards. The low rates of SBM produced unacceptably lower crop yields for the site. Acceptable rates of SBM (from a crop yield point of view) resulted in similar  $\text{NO}_3^-$  - N concentrations ( $\approx 14.0$  mg  $\text{NO}_3^-$  - N  $\text{L}^{-1}$ ) as optimal rates of fertilizer and LCM. Application rates higher than recommended resulted in significantly higher concentrations of  $\text{NO}_3^-$  - N.

These data clearly show that LCM should not be spread in the fall. Crop yields at the highest fall application rate were significantly lower (0.6 - 1.0 t  $\text{ha}^{-1}$ ) than the lowest spring application rate. Conversely, the lowest fall application rate had  $\text{NO}_3^-$  - N concentrations in the leaching water ( $\approx 20.0$  mg N  $\text{L}^{-1}$ ) that were higher than the highest spring application rate. Thus, fall application should be avoided for both economic and environmental reasons.

This study suggests that for conditions similar to the Elora site, it is going to be very difficult to reconcile environmental and economic priorities. The high base line leaching concentrations ( $6.4 \text{ mg NO}_3^- - \text{N L}^{-1}$ ) leaves little room for error in N management. The optimum N fertilizer rates for crop yield resulted in leaching water with  $14 \text{ mg NO}_3^- - \text{N L}^{-1}$ . However, decreasing fertilizer N rates by 50 % only decreased the N concentrations to  $12.3 \text{ mg NO}_3^- - \text{N L}^{-1}$ . This low rate of fertilizer application is not economical for farmers.

As expected, the amounts of mineral soil N indicated similar significant differences as were observed with the solution sampler concentrations of  $\text{NO}_3^-$ . Little mineral  $\text{NH}_4^+$  was found in the soil profile except right after N application. The disappearance of this  $\text{NH}_4^+$  within three weeks and the low measured  $\text{NH}_4^+$  concentration in the soil solution suggested that nitrification occurs very rapidly at this site. In addition, it was observed that the soil solution concentrations were a function of the amount of mineral N in the profile. All three N sources and the control plots had equal amounts of mineral N in the soil profile before spring N application. However, the  $\text{NH}_4\text{NO}_3$  treated plots had the most mineral N remaining after harvest.

Denitrification results were consistent with soil solution and mineral N measurements. Over a two month period after N application in the spring of 1993, denitrification losses from the high N rate treated plots were 2.2, 3.2, 29.5 and  $115.0 \text{ kg N ha}^{-1}$  for the control,  $\text{NH}_4\text{NO}_3$ , LCM and SBM treated plots, respectively. In addition, the rapid decrease of denitrifying enzyme activity with depth suggested that the denitrifying bacteria do not survive below the 30 cm depth at this site. Measurements using  $^{15}\text{N}$  labelled  $\text{NH}_4^+$  in manure and mineral fertilizer plots confirm that volatilization losses in manure were significant but not as significant as leaching or denitrification losses.

In keeping with several recent reports, it was suggested that increased research into feed ingredients of livestock may lead to lower N containing manures. In addition, it was emphasized that long term manure research plots be installed to study the complete system of manure management so that the relationships between the microbial biomass, soil, plants and atmosphere can be properly understood

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# Chapter 1 Introduction

## 1.1 Introduction

This study examined nitrate leaching out of the root zone and nitrogen supply to corn from two types of manure and from inorganic nitrogen fertilizer. The study took place on a silt loam soil at the Ontario Ministry of Agriculture and Food Research Station, Elora, ON. The soils of this area have developed from a variety of glacial deposits and thus consist of a wide range of textures and drainage classes. The area has been traditionally cropped to corn which is used to supply the increasing amount of livestock operations in the area.

The manure produced by livestock in Ontario represents a significant nitrogen resource. Based on 1987 levels of production,  $3 \times 10^7$  tonnes of manure containing  $1.3 \times 10^5$  tonnes of nitrogen (N) are produced annually. Livestock wastes have been traditionally returned to the land on the farm where they were produced and where the major portion of the feed was produced. Excessive rates of manure application can be avoided by applying manure to an appropriately large landbase. Agricultural specialization has resulted in larger livestock operations on smaller landbases in which much of the feed is imported to the farm. These large operations result in the production of quantities of manure nitrogen in excess of that required by the associated cropped land. The costs associated with transport and handling of this manure is high and therefore the export value is low. Disposal of the manure, at rates of application in excess of that required by the crops, is often the most economically viable option. Once disposal has become the objective, there may be little concern for the effect of rate, timing or method of application on the availability of nutrients to crops. In these situations, the nutrient content of the manure is often ignored when assessing the fertilizer requirement of the crop. Many farmers discount the N contained in manure and apply additional amounts of inorganic nitrogen, further increasing the N loading.

The application of animal manure at excessively high rates or the combined application of high rates of manure and nitrogen fertilizer increases the potential for nitrate accumulation in soil and contamination of surface water and groundwater. There are numerous isolated measurements

of elevated groundwater  $\text{NO}_3^-$  concentrations in Ontario that are attributable to the application of nitrogen either as manure or in combination with fertilizer N. A recent study of well water quality in Ontario prepared for Agriculture Canada, with support from the OME, indicated that in 13 % of the well water samples collected from agricultural wells in 1991 - 1992,  $\text{NO}_3^-$  - N was present in concentrations in excess of  $10 \text{ mg N L}^{-1}$  (Working Committee of the OFGQS, 1992). Groundwater samples collected using multilevel sampling probes on 144 sites<sup>1</sup> indicated that 44 % of the sites had  $\text{NO}_3^-$ -N in excess of  $10 \text{ mg N L}^{-1}$ . On farms utilizing animal manures, groundwater samples indicated that 52 % of the sites had nitrate concentrations in excess of  $10 \text{ mg N L}^{-1}$  in at least one depth as compared to 41 % in sites where manure had not been applied. The application of animal manure also resulted in a dramatic increase in faecal coliform counts (Working Committee of the OFGQS, 1992).

Guidelines as to acceptable rates of manure application alone or in combination with synthetic N fertilizer are not well defined. The Agricultural Code of Practice for Ontario was designed, in part, to reduce the impact of livestock wastes, on water quality, to acceptable levels. The Code of Practice established minimum land areas for livestock operations based on the nitrogen in the manure. Manure-N applications amounting to twice that required by the crop are permitted. This is based on the premise that only half of the nitrogen would be available to the crop in the year of application. It is not clear whether continued application of manure at this rate would result in groundwater contamination. These guidelines do not explicitly evaluate the potential for nitrate contamination of groundwater. More recently "Best Management Practices" guidelines for livestock and poultry waste management have been published under the joint authorship of Agriculture Canada and the Ontario Ministry of Agriculture and Food. This document recommends that only 75 % of the crop requirements for nitrogen be supplied from manure and the remainder be supplied from synthetic N fertilizers. It is important that clear and consistent

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<sup>1</sup>The well water survey used two methods of examining  $\text{NO}_3^-$  movement to groundwater: well water samples and groundwater samples collected using multilevel sampling probes. In 36% of the sites where both methods were used the multilevel samplers indicated a higher  $\text{NO}_3^-$  concentration in at least one of the sampling depths than acceptable for drinking water.



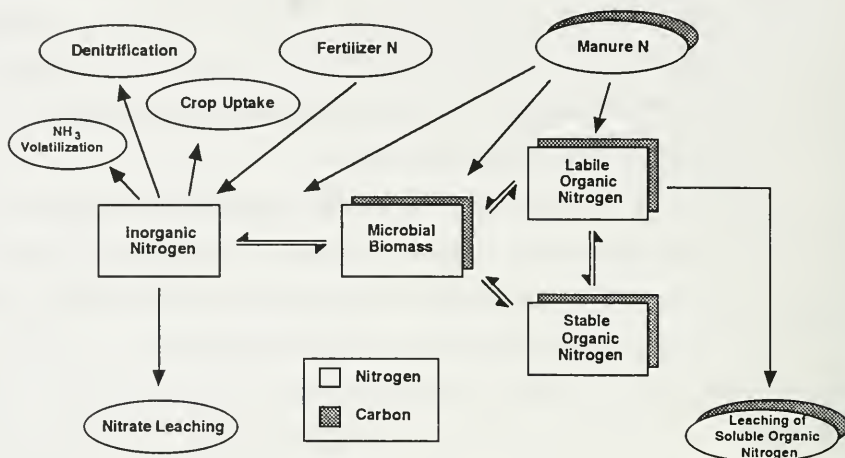
guidelines for acceptable rates of manure application be developed. These guidelines must be based on agronomic, environmental and economic considerations. Of particular concern is the potential for  $\text{NO}_3^-$  contamination of groundwater. To ensure adequate protection of our groundwater resource, it is imperative that the potential for groundwater contamination be evaluated in determining acceptable rates of manure application to land.

Evaluation of the amount of manure which can safely be applied to soil and not result in nitrate contamination of groundwater<sup>2</sup>, requires a determination of the fate of manure N in soil. The fate of manure N is strongly influenced by the carbon content of the manure. The organic materials contained in manure act as substrates for the soil microflora which impacts the extent of microbial processes influencing the fate of manure N (Figure 1.1). Manures differ from inorganic fertilizers which do not contain organic substrates. Denitrification is an important pathway by which nitrogen may be lost from soil. The loss of nitrogen represents both a decrease in plant available N and a removal of potentially leachable nitrate. Increased carbon inputs associated with manure application may increase the extent of denitrification in the soil profile and thus reduce the potential for nitrate contamination of groundwater. Therefore, an accurate evaluation of the relationship between manure application and the potential for groundwater contamination requires that the impact of manure application on denitrification rates be known. In addition, it is imperative that the flux of water draining from the root zone and the amount of N in the soil be known. Therefore, it becomes obvious that the timing and amount of plant N uptake is also required to estimate the potential of  $\text{NO}_3^-$  contamination of groundwater.

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<sup>2</sup>The potential for surface- and ground-water contamination by other contaminants, such as faecal coliforms, must also be evaluated. Here we are limiting our discussion to nitrate contamination.

Figure 1.1: A schematic representation of the relationship between manure application and the sources and sinks for nitrogen in soil with reference to carbon cycling.



## 1.2 Objectives

The objectives of this research were:

1. To determine the quantities of nitrate ( $\text{NO}_3^-$ ) and dissolved organic carbon (DOC) transported below the root zone from crops treated with different levels of N from manures and fertilizer in relation to crop production.
2. To establish the influence of the time and manure application on crop response and  $\text{NO}_3^-$  contribution to groundwater.
3. To evaluate the potential for denitrification in relation to transported  $\text{NO}_3^-$  and DOC below the root zone and into the water table from manures applied in the fall and spring.



### 1.3 Background

This section highlights some of the background information necessary for understanding the concerns for nitrate contamination of groundwater and the nitrogen processes in manured soils. This chapter does not attempt to provide a thorough review of the literature.

#### 1.3.1 Adverse Health Effects

Concern about elevated levels of  $\text{NO}_3^-$  in groundwater relate primarily to  $\text{NO}_3^-$  concentration in drinking water and human health. Approximately 26 % of Canadians and half the communities in Ontario rely upon groundwater as the source of their drinking water (Science Council of Canada, 1988). Maintaining the quality of this resource is of utmost importance if we wish to continue using groundwater as a source of drinking water. One of the major concerns about the quality of drinking water is the concentration of  $\text{NO}_3^-$ . Environment Canada has set the drinking water standard at no more than  $10 \text{ mg NO}_3^- \cdot \text{N L}^{-1}$  (Environment Canada, 1987). Concentrations of  $\text{NO}_3^-$  in drinking water in excess of  $10 \text{ mg N L}^{-1}$  have been related to the incidence of clinical methaemoglobinaemia (blue baby syndrome) and stomach cancers. However, fewer than 10 cases have been reported in the last 40 years.

##### 1.3.1.1 Methaemoglobinaemia

Ingested nitrate may be absorbed into the blood in the stomach or upper intestine. Most of the adsorbed nitrate is excreted as urine but some may be reduced to nitrite, especially in the intestine. It is nitrite ( $\text{NO}_2^-$ ) which poses a threat to human health. Nitrite oxidizes the iron moieties contained in normal oxyhemoglobin to produce methemoglobin (metHb). The oxygen binding capacity of metHb is significantly less than normal hemoglobin and if more than 10 % of the hemoglobin is converted to metHb then the oxygen carrying capacity of the blood is lessened and the symptoms of anoxia may develop (Shuval and Gruener, 1977). In very young children, fetal hemoglobin persists in the blood stream and is more susceptible to nitrite oxidation (van der Heijden and Montizaan, 1988). The activity of the enzyme that reduces metHb to hemoglobin is

lower in infants. In addition, the higher pH of the stomach fluids promotes bacterial activity which increases the reduction of nitrate to nitrite (Keeney and Follett, 1991).

#### 1.3.1.2 Stomach Cancer

A somewhat more tenuous link has been made between  $\text{NO}_3^-$  ingestion and the incidence of stomach cancer (Fletcher, 1991). Nitrate can react with secondary amines to produce N-nitroso compounds which it has been suggested may increase the risk of stomach cancers (Addiscott et al., 1991). There is little evidence linking the concentrations of  $\text{NO}_3^-$  in drinking water and stomach cancer. Indeed some studies have found nitrate to be negatively related to the incidence of stomach cancer (Risch et al., 1985). The main source of nitrate in the adult diet is food, with only approximately 1 % from water unless the water supply is exceptionally high in nitrate. None the less, chronic exposure to elevated levels of  $\text{NO}_3^-$  in drinking water is of concern.

#### 1.3.2 Environmental Effects

In addition to adverse effects on human and animal health, elevated nitrate concentration in surface waters may contribute to eutrophication of lakes and streams. Eutrophication is traditionally associated with phosphorus runoff. In phosphorus laden waters, blue-green bacteria are able to proliferate obtaining the nitrogen required from the fixation of atmospheric  $\text{N}_2$ . Nitrate provides a more readily available N source allowing for an increased growth rate and thus more rapid  $\text{O}_2$  consumption. Nitrogen in surface waters is susceptible to the denitrification pathway which has various nitrogen containing gases, such as  $\text{N}_2\text{O}$  and  $\text{NO}$ , as its products. Recently, much attention is being given to these gases as they are thought to be involved with the depletion of atmospheric ozone and the greenhouse warming phenomenon.

### 1.3.3 Nitrogen Processes in Manured Soils

#### 1.3.3.1 Sources of Nitrogen

Nitrate in groundwater may be derived from a number of industrial, municipal, residential and agricultural sources. Only in a few cases have the relative contributions of each of these sources been adequately evaluated. The relative contributions, from each of these sources, are likely to change with geographic region, land use and climate. The work presented here only addresses agricultural contributions to groundwater nitrate. This does not imply that this is the largest or most important source of nitrate.

The loss of nitrate from the root zone to the groundwater is not unique to agricultural systems; it likely occurs in all ecosystems to a greater or lesser degree. The magnitude of nitrate loss is a function of the ability of the soil - plant system to retain N in the root zone. Over the past century there has been a concerted effort to increase the yield of agricultural crops. This has been achieved by improved plant varieties, development of pest management practices and by reducing nutrient limitation through the widespread application of inorganic fertilizers and animal manures. The total amount of N fertilizer used in Ontario has increased from approximately 40,000 tonnes in 1961 to 200,000 tonnes in 1989. This has resulted from the application of increased rates of N fertilizer as well as the application of N fertilizer to a larger landbase. The increased rate of fertilizer N application has resulted in significant increases in crop production but increased availability of N to the plant has also increased the potential for nitrate loss to groundwater. Thus, the past three decades' increase in productivity has been combined with an increase in the potential for nitrate contamination of groundwater.

With the advent of low cost synthetic fertilizers, the use of animal manures as N fertilizers became less cost effective. However, in recent years, synthetic fertilizers have become more expensive and manure use has, once again, become more economical. Manure is a source of all plant nutrients and it is a soil conditioner (Bouldin et al., 1984). In most situations, crop response cannot be entirely attributed to N, although the major response of crops to manure is usually associated with the N supply from the manure. Many pathways are followed by N during animal

waste use and conversion. The processes of conversion (mineralization, decomposition, denitrification) involve physical, chemical and biological reactions. Microorganisms play a major role in the conversion of manure to inorganic N in the soil.

The N in fresh manure is in the form of urea,  $\text{NH}_3$  and organic N. The amount and type of N depends on the age, type and handling process of the manure. Anaerobically stored manures (liquid) have a higher percentage of ammonium, ( $\text{NH}_4^+$ ), due to reduced nitrification and continued mineralization of organic N. In aerobically stored manures (solid), the N is subject to  $\text{NH}_3$  volatilization, nitrification, leaching, denitrification and immobilization (Paul, 1991). Table 1.1 gives some typical chemical characteristics of various manures.

Table 1.1: Chemical characteristics of various manures.

Manure	Total N	$\text{NH}_4^+$ - N	$\text{NO}_3^-$ - N	Dry Matter	C/N Ratio	pH	Source
-----(% wet basis)-----							
LCM*	0.34	0.20	neg**	6.00	7.09	6.95	Paul, 1991
	0.44	0.25	neg	8.00	7.13	7.25	Paul, 1991
	0.18	0.07	na**	4.54	na	na	Sutton et al., 1986
SBM*	0.38	0.11	neg	13.0	13.9	8.7	Paul, 1991
	0.64	0.16	na	25.2	na	na	Sutton et al., 1986

\* LCM - Liquid Dairy Cattle Manure; SBM - Solid Beef Manure

\*\* neg - negligible; na - not available

### 1.3.3.2 Nitrogen Leaching

To be lost via leaching, nitrogen must be present in a water soluble and mobile form such as  $\text{NH}_4^+$  or  $\text{NO}_3^-$ , thus allowing it to be transported with percolating water. The following discussion will be based on the movement of  $\text{NO}_3^-$  since the movement of  $\text{NH}_4^+$ , a cation, is retarded by the cation exchange capacity associated with negatively charged clay minerals and soil organic matter in

most soils. The amount of  $\text{NO}_3^-$  accumulating in the soil, and thus available to be leached from it, is dependent upon the net effect of several processes in the nitrogen cycle (Figure 1.1). The transformations affecting  $\text{NO}_3^-$  occur simultaneously with transport through the profile. The extent to which the various biochemical processes impact on  $\text{NO}_3^-$  concentration will vary throughout the soil profile as a result of changes in the soil - plant environment and the resulting impact on microbial activity. Thus, evaluation of the extent of nitrate movement must consider the simultaneous occurrence of transport and transformation. The net effect of these processes, and thus the potential for nitrate movement from the root zone to groundwater, depends on climate, soil type and land use.

#### 1.3.3.2.1 Climate

Nitrate movement below the root zone only occurs when there is net drainage. This occurs when precipitation exceeds evapotranspiration, storage and runoff. The extent and timing of periods of drainage depend upon the climate. In Southern Ontario, precipitation exceeds evapotranspiration during the spring and fall causing net drainage of water out of the root zone during these periods. On average, it has been estimated that the total net drainage, under the climatic conditions in Southern Ontario, is approximately 160 mm (Goss et al., 1992). Due to annual variations in climate, the extent to which potential nitrate loss will be realized will vary. Management strategies which minimize nitrate accumulation during high leaching risk periods will, in the long-term, reduce nitrate loss to the groundwater.

#### 1.3.3.2.2 Soil Type

Soil texture and soil structure influences biological activity and the rate at which solutes are transported through the soil profile. Soil nitrate originates from N fertilizers, atmospheric deposition of N and from the mineralization of crop residues, animal manures and soil organic matter. Nitrate which accumulates in soil can remain in the there, be taken up by the plant and / or microbial biomass, be denitrified or be leached from the profile. These processes are influenced by

the rate at which water transports  $\text{NO}_3^-$  through the soil. The more rapidly  $\text{NO}_3^-$  is transported out of the soil profile, the less opportunity there is for reactions, which operate as a sink for  $\text{NO}_3^-$  (plant uptake, denitrification), to remove it from the soil solution. Texture has a strong influence on soil hydraulic properties. Fine-textured soils have a low water infiltration rate and thus processes which occur at the surface (runoff) or in the upper profile (plant uptake or denitrification) have greater opportunity to occur due the time required for water to pass through the profile. In coarse-textured soils, the rate of percolation is much higher and, when sufficient rainfall occurs, the leaching of nitrate through the profile may be very rapid.

Texture also influences soil biological activity. Coarse-textured soils have a high air filled porosity and as a result aerobic processes predominate. Denitrification reduces nitrate to nitrogen gas ( $\text{N}_2$ ) and occurs in anoxic zones in the soil profile. The aerobic nature of coarse-textured soils reduces the potential for denitrification loss, and, by reducing this sink for  $\text{NO}_3^-$ , increases the potential for  $\text{NO}_3^-$  contamination of groundwater. The low water holding capacity of coarse textured soils may cause water availability to limit microbial activity and reduce N mineralization.

#### 1.3.3.2.3 Management System

The accumulation of nitrate in the soil increases the risk of nitrate loss to groundwater. Management strategies which limit the amount of nitrate in the soil at any one time will reduce the potential for loss. Choice of the rate, timing and formulation of N application have an important impact on nitrate accumulation in soil.

The rate of nitrogen fertilizer application clearly impacts upon the amount of  $\text{NO}_3^-$  accumulating in the soil. The use of excessively high rates of fertilizer N not only increases the risk of nitrate contamination of groundwater but also is unprofitable for the producer. Determination of nitrogen fertilizer application rates in Ontario have been based on the maximum economic return. Prior to 1991, this rate had been based on an expected yield goal, climatic region and previous management. Recently a spring nitrate soil test for corn has been introduced in Ontario (Kachanoski and Beauchamp, 1991). This test estimates the maximum economic rate of N fertilizer



(MERN) based on the amount of nitrate in the top 60 cm at the time of planting. This test is based on an empirical relationship between MERN and spring soil N test values on 60-70 test sites conducted under the Tillage 2000, Partners in Nitrogen and other programs funded by the Ontario Ministry of Agriculture and Food. By accounting for the amount of nitrate carried over from the previous year and N mineralized up to the time of planting, the amount of applied fertilizer can be adjusted to meet the crop requirements.

The form of nitrogen applied can also affect the potential for nitrate loss. The application of fertilizers containing a high percentage of ammoniacal or ammoniacal producing forms of nitrogen (Urea, urea ammonium nitrate, anhydrous ammonia) delay the formation of nitrate and thus reduce the potential for loss during this period. Similarly the use of nitrification inhibitors in combination with ammoniacal N sources delay nitrification (the conversion of ammonium to nitrate) and reduces the potential for nitrate loss. Banding of urea and ammonium-based fertilizers also delays nitrification and reduces the potential for nitrate loss. It has long been recognized that delaying nitrogen fertilizer application results in increased availability to the plant and reduced potential for  $\text{NO}_3^-$  leaching. Split applications of N fertilizer, at the time of planting and at the 6-8 leaf stage, is a commonly used approach to increase fertilizer availability to the plant. Crop rotation has also been shown to reduce the amount of N available for leaching.

Tillage affects the potential for nitrate leaching by altering the rate of residue breakdown and by disrupting soil macropores. Crop residues left on the soil surface reflect light and insulate soil, reducing soil temperature and loss of water through evaporation (Bond and Willis, 1969). This creates a favorable environment for microbial activity in soils that normally tend to be warm and dry (Power et al., 1986). Crop residues also serve as a carbon and nitrogen substrate, which is decomposed through microbial activity. In an undisturbed system, most N released during oxidation of organic matter is assimilated into microbial biomass, taken up by plants, or conserved as surface litter (Doran and Smith, 1987). Tillage alters this steady state by increasing soil aeration, removing the insulating effect on evaporation and temperature, and distributing the organic substrate throughout the plow layer (Van Veen and Paul, 1981). This increases the accessibility of the

organic substrate to decomposition by soil microorganisms, and thus increases mineralization (Elliott, 1986). The incorporation of residues in the soil associated with conventional tillage practices increases the rate of breakdown relative to conservation tillage practices where residues accumulate on the soil surface. Rapid decomposition results in the mineralization of nitrogen, increasing nitrate availability to the plant and the potential for nitrate loss from the profile. If crop residue breakdown occurs when there is no actively growing crop, nitrate will accumulate in the soil and may be leached from the profile. Thus, by retaining nitrogen in crop residues, conservation tillage practices may reduce leaching of nitrate over the fall to spring period following the incorporation of crop residues under conventional tillage. In addition to incorporating crop residues, tillage disrupts the continuous pores and channels which form as a result of plant root growth and earthworm activity. In fine-textured soils, these channels may be the major pathways of water percolation (Edwards et al., 1989). Disruption of the continuous channels will slow water movement through the soil and increase the availability of N to the processes occurring at or near the surface (runoff, plant uptake, denitrification). Thus, tillage may decrease the rate of water movement and the amount of N moving through fine-textured soils.

Long-term comparisons of tillage have indicated that with adequate applications of N fertilizer, greater or equal corn yields can be achieved under no-tillage than conventional tillage. Yields of corn under no tillage systems are generally lower when small amounts of fertilizer N are added, but approximately equal when amounts in excess of  $100 \text{ kg N ha}^{-1}$  are added (Doran and Power, 1983; Meisinger et al., 1985; Thomas and Frye, 1984). This has been attributed to greater immobilization of fertilizer N and less mineralization of soil N in no tillage soils (Kitur et al., 1984; Rice and Smith, 1984). Immobilization is a storage process, not a loss, so that over a long period, yield response of no tillage crops may be comparable to those of conventionally tilled crops at low rates of N fertilizer application. The placement of fertilizer N below the surface layer of no tillage soils, where biomass levels and concentration of high C:N substrates are lower, can increase immediate N availability, N uptake and crop yields (Doran and Smith, 1987; Mengel et al., 1982).



#### 1.3.3.3 Ammonia Volatilization

While losses of  $\text{NH}_3$  during handling and storage of manures are known to occur, significant losses of  $\text{NH}_3$  from field applied manure have also been reported (Beauchamp, 1983; Adriano et al., 1974). In addition, the proportion of  $\text{NH}_3$  that is lost and the rate of loss are both extremely variable. Ammonia volatilization and its variability are influenced by methods of measurement, temperature, manure pH, type of manure application, soil water content, manure chemical content, climatic variables and soil physical and chemical properties.

Estimates of  $\text{NH}_3$  volatilization vary, but it is often assumed that 50 % of manure N is lost through this process (Bouldin et al., 1984). Lauer et al. (1976) reported losses of 61 to 99 % in 5 to 25 days after application of solid dairy cattle manure applied in early spring. From 24 to 33 % of applied  $\text{NH}_3$  - N in liquid dairy cattle manure was volatilized during a six day period in May in a 3 year study at the Elora Research Station in Ontario (Beauchamp et al., 1982). Incorporation of manure usually results in a significant decrease in  $\text{NH}_3$  loss (Hoff et al., 1981). Van der Molen et al. (1990) found that injected manure resulted in an 11 and 16 % loss compared with 32 and 67% loss, respectively, in unincorporated manure during 9 days of two experiments.

#### 1.3.3.4 Nitrification

Nitrification is a two stage oxidation process of  $\text{NH}_4^+$  to  $\text{NO}_2^-$  and  $\text{NO}_2^-$  to  $\text{NO}_3^-$  involving two groups of microorganisms. If there are available sources of energy and carbon, much of the  $\text{NH}_4^+$  derived from decomposition of organic matter would be assimilated into new microbial biomass. However, in most cases, energy and available C are limiting and not all of the available  $\text{NH}_4^+$  is assimilated. The  $\text{NH}_4^+$  in excess of microbial demand is released to the soil environment where it is quickly oxidized to  $\text{NO}_3^-$ . The main factors which limit nitrification are availability of  $\text{NH}_4^+$ , pH,  $\text{CO}_2$ ,  $\text{O}_2$  and temperature. Microbial activity and nitrification are a maximum when  $\theta_v$  approaches 60 % of saturation and nitrification decreases rapidly as anaerobic conditions dominate at  $\theta_v$  values greater than 80 % of saturation.

Comfort et al. (1988) found that  $\text{NO}_3^-$  concentrations reached a maximum 67 days after application of liquid dairy cattle manure. The distribution of nitrate at this time was similar to the original distribution of  $\text{NH}_4^+$  at the time of manure application. Adriano et al. (1974) found that nitrification was delayed by 2 to 4 weeks after dairy cattle manure was mixed with soil. The delay in nitrification has been observed by other researchers and has been attributed to high levels of  $\text{NH}_4^+$ ,  $\text{NH}_3$  and pH which are toxic to several of the nitrifying microorganisms.

#### 1.3.3.5 Denitrification

Denitrification is the conversion of  $\text{NO}_3^-$  to gaseous N, in the form of  $\text{N}_2$ , or the intermediates of NO and  $\text{N}_2\text{O}$ . The requirements for denitrification include denitrifying bacteria, readily available carbon for energy, anaerobic conditions and nitrate. Denitrification losses increase in soils amended with manures because the manure provides energy for the denitrifying bacteria, oxygen consumption increases and manures are capable of sealing the soil surface (Paul et al., 1991). The last two reasons increase denitrification by promoting anaerobic microsites in the soil. Denitrification is difficult to measure in the field because of the rapid and fluctuating rates. Results of denitrification rates measured from soil cores in the laboratory must be extrapolated to the field soil.

Fresh manure contains very little  $\text{NO}_3^-$  - N and thus there is a low potential for denitrification. However, as soon as the manure is incorporated into the soil, decomposition begins and  $\text{NO}_3^-$  is produced which is then susceptible to denitrification. Denitrification may occur to a greater extent in manure fertilized soils than in inorganic fertilized soils due to the abundant C which acts as an energy source (Smith and Peterson, 1982). Denitrification is strongly dependent on soil aeration so that the denitrification potential increases as the soil drainage decreases to poorly drained. Denitrification losses would be expected to be a maximum at higher application rates ( $>100 \text{ tonnes ha}^{-1}$ ) where there is abundant C and  $\text{NO}_3^-$  and, in addition, low redox potential due to intense microbial activity (Smith and Peterson, 1982).

Thompson et al. (1987) measured denitrification losses of 33.6 and 57.9 kg N ha<sup>-1</sup> for surface applied and injected manures, respectively. The surface and injected control plots had losses of 3.7 and 5.7 kg N ha<sup>-1</sup>, respectively. Denitrification rates increase with increasing clay content of the soil. Webster and Dowdell (1982) consistently measured higher N<sub>2</sub>O losses from a clay soil compared to a silt loam. Burton et al. (1993) measured similar denitrification patterns between a silt loam and a sand. Denitrification has been found to be negligible below a soil water content,  $\theta_v$ , of approximately 60 % of saturation and does not reach a maximum until a  $\theta_v$  of 80 % of saturation (Linn and Doran, 1984). However, denitrification has also been measured in finer textured soils with a  $\theta_v$  less than 60 % of saturation and has been attributed to anaerobic microsites. In addition to denitrification, N<sub>2</sub>O is also lost during nitrification although it appears to a much lesser degree than during denitrification (Paul et al., 1991).

Denitrification from manured soils, if substantial may reduce the leaching of NO<sub>3</sub><sup>-</sup>, yet, few studies have measured both denitrification and leaching at the same time. In one such study, Lowrance (1992) measured N outputs (surface runoff, subsurface flow and denitrification) from a cropped agricultural watershed. The average annual denitrification loss was 7.8 kg N ha<sup>-1</sup>. Denitrification and surface runoff losses together were approximately 20 % of that lost by subsurface flow. In an indirect approach, Addiscott and Powlson (1992) partitioned losses of <sup>15</sup>N-labelled fertilizer applied to winter wheat in 13 experiments. They used a leaching model to compute leaching losses, and obtained denitrification losses by difference. Apparent losses of denitrification were on average nearly twice as large as those by leaching, but the ratio varied greatly between experiments.

There is also current interest in the effect of manure application on production of nitrous oxide (N<sub>2</sub>O) in soil, because of the role of N<sub>2</sub>O in atmospheric ozone degradation and as a greenhouse gas. Studies such as those of Cates and Keeney (1987) and Christensen (1983) have described episodic denitrification and N<sub>2</sub>O production resulting from manure application. Nevertheless, specific information about regulation of denitrification on manured sites is lacking. For example, C supply to denitrifiers from manure is expected to be a principal determinant of N

gas production. Yet, the supply of substrate C available to denitrifiers in situ is difficult to characterize (Focht, 1974; Schipper et al., 1993). The factors which determine the amount of  $\text{N}_2\text{O}$  (versus  $\text{N}_2$ ) produced from denitrification are also poorly understood. Finally, estimation of episodic denitrification and  $\text{N}_2\text{O}$  production from manure application is very imprecise unless measurements are made at very frequent intervals. A more detailed understanding of regulation of episodic N gas production will contribute to modelling N gas production in instances when frequent measurements cannot be made.

#### 1.3.3.6 Mineralization and Immobilization

Transformations from the various forms of N to  $\text{NH}_4^+$  and then to  $\text{NO}_3^-$  begins as soon as the manure is applied to the soil (Smith and Peterson, 1982). Excessive rates of manure can allow  $\text{NH}_3$  to temporarily accumulate which slow the formation of  $\text{NH}_4^+$  and  $\text{NO}_3^-$ . Since mineralization of the organic N must occur before the N is available to plants, mineralization rates are key to the application rates of manure. A decay series can be used to express the amount of N mineralized each year after fertilization with manure. For example, the decay series of 0.30, 0.10, 0.05 means that 30 % of the N is mineralized during the first year after application of manure, 10 % is mineralized the second year and 5 % each subsequent year. These decay series indicate that constant annual manure applications that supply enough N for the present crop will cause excessive fertilization. Therefore, decreasing amounts of manure must be applied to meet the needs of subsequent crops. Poultry manure has been found to have decay series of 0.85, 0.10 and 0.05 while fresh dairy and beef wastes have decay series of approximately 0.70, 0.15, 0.10 and 0.05 (Pratt et al., 1973). These decay series are useful for general comparisons between manure types but they must be used with caution as they were developed under different climatic and soil conditions.

Manure inorganic N may be immobilized into the microbial biomass and then later mineralized. Comfort et al. (1988) found that 50 % of applied inorganic N, from dairy cattle slurry injected to a silt loam, was unaccounted for within 5 days of injection. After 15 days, the amount of

inorganic N was similar to that at the time of injection. They proposed that immobilization and subsequent mineralization was the cause of the temporary deficit of inorganic N. Persson (1988) reported that 50 % of  $^{15}\text{N}$  labelled dairy cattle slurry  $\text{NH}_4^+$  was immobilized after 4 weeks of incubation. Very little N was immobilized in the soil that received inorganic N and 38 % of the immobilized labelled organic N remineralized after 141 days during the growth of a sugar beet crop.

## Chapter 2 Materials and Methods

### 2.1 Introduction

This chapter contains a general overview of the geographic location of the experiment, the materials and methods used for the various measurements and an explanation of the experimental design. Figure 2.1 gives a diagrammatic representation of the objectives, design and measurements made throughout this study.

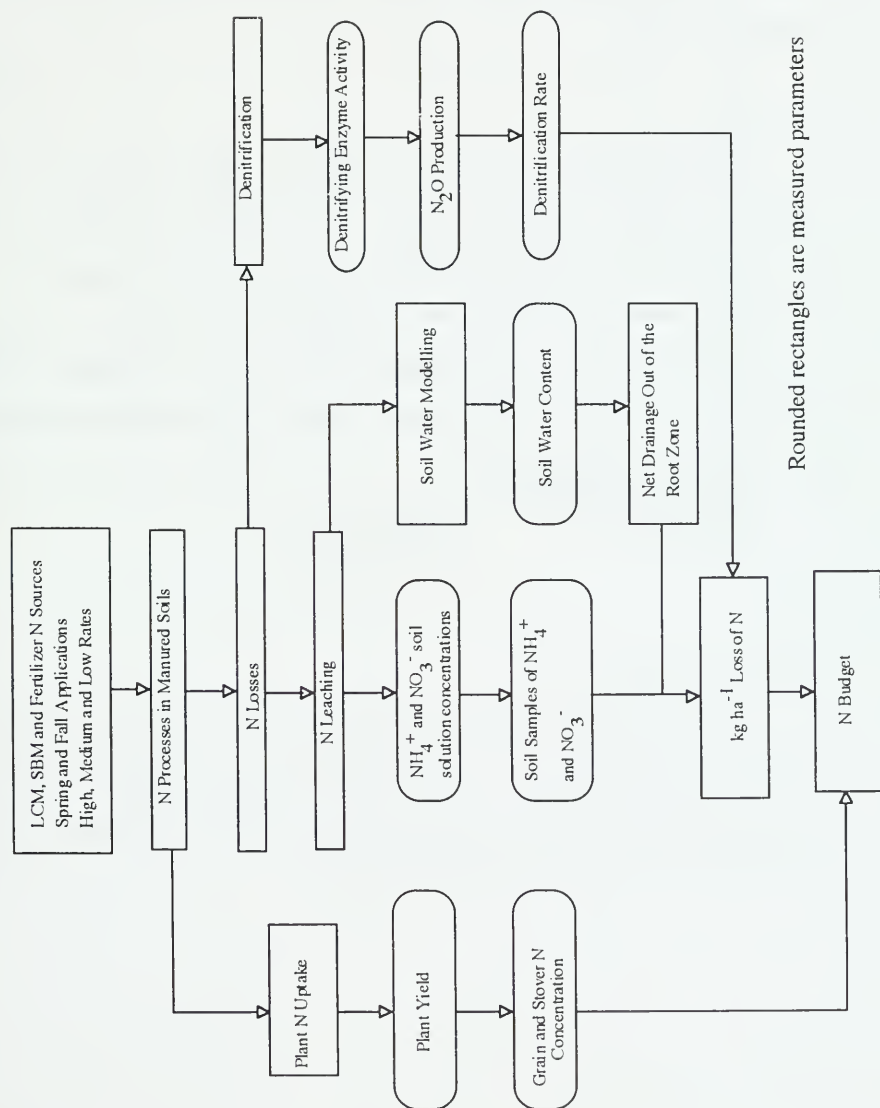
### 2.2 General Site Description

#### 2.2.1 Soils

This study was conducted at the Ontario Ministry of Agriculture Elora Research Station (43° 39' N 80° 25' W; 376 m.a.s.l.). The underlying bedrock of this area is sedimentary rock from the Silurian and Devonian ages and includes sandstone, shale, dolomite and limestone. The bedrock is only visible in some road and river cuts due to the thick cover of surficial materials. The surficial deposits of the surrounding area reflect the influences of continental glaciation (drumlins, eskers, moraines and glacial tills) which has produced an undulating topography. The range of parent materials from well drained outwash sediments to poorly drained lacustrine deposits have resulted in soils with a variety of textures and drainage classes.

The soils found on the station are part of the Woolwich and Guelph catenas. The Woolwich catena includes the well drained Woolwich series, the imperfectly drained Conestogo series and the poorly drained Maryhill series (Presant and Wicklund, 1971). The Guelph catena includes the well drained Guelph series, the imperfectly drained London series and the poorly drained Parkhill series (Hoffman et al., 1963). The study, reported here, took place on the lower slope position of a Conestogo silt loam (Gleyed Melanic Brunisol) which was not tile drained. The site had been in continuous corn for 10 - 15 years prior to this experiment. This soil is closely associated with the London loam of the Guelph catena from which it differs only by a slight change in parent material (Presant and Wicklund, 1971). The parent material of the Conestogo silt loam is

Figure 2.1: Diagrammatic representation of project objectives, design and measurements.





composed of alluvial and lacustrine deposits overlying a calcareous glacial till. The parent material of the London loam consists of only the calcareous glacial till which is derived from the underlying bedrock. A detailed description of the physical and chemical properties of the Conestogo silt loam is given in Chapter 3.

## 2.2.2 Climate

Wellington County has a climate that is classified as a continental climate which is modified somewhat by the Great Lakes. The area receives approximately 2500 corn heat units (CHU) and has a growing season of approximately 200 days (Brown et al., 1968). Environment Canada maintains a weather observation station at this site which allowed comparisons to be made between the air temperature and precipitation throughout this study with the 1951-1980 climate precipitation and temperature normals. This data is available in a variety of formats from the following address:

Agroclimatology Program  
c/o Land Resource Science  
University of Guelph  
Guelph, Ontario  
N1G 2W1

ph: 519-824-4120  
fax: 519-824-5730

### 2.2.2.1 Air Temperature

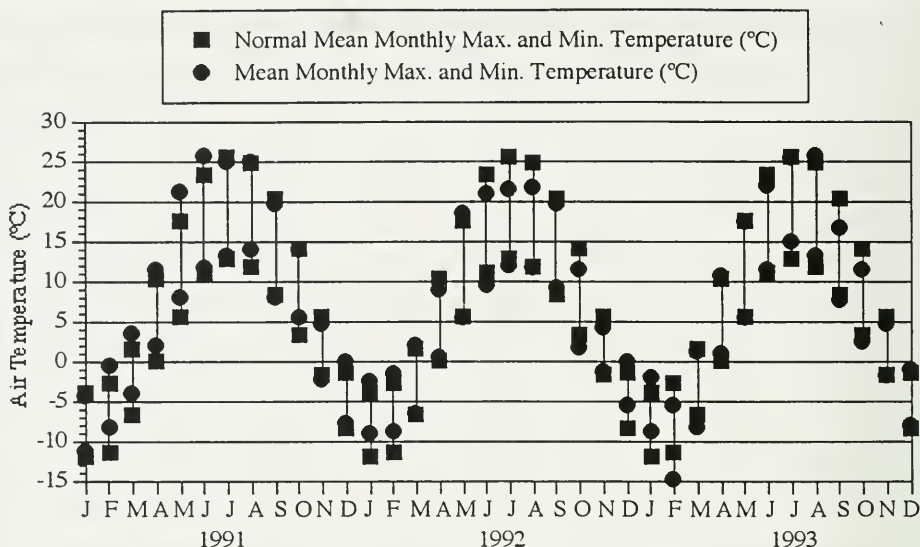
Table 2.1 gives the maximum and minimum daily temperatures for the 30 year period (1951-1980) and for the three year period during this study. This information is given in Figure 2.2. Air temperatures throughout the study were similar to the 30 year normals except for slightly lower maximum temperatures during the 1992 summer.



Table 2.1: Mean monthly maximum and minimum air temperature (°C) for the 1951-1980 period and for the three years of this study as recorded at the Elora Research Station.

Month	1951-1980		1991		1992		1993	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
January	-4.1	-12.2	-4.3	-11.4	-2.5	-9.0	-2.0	-8.8
February	-2.9	-11.7	-0.7	-8.4	-1.6	-8.9	-5.7	-14.8
March	1.5	-6.9	3.4	-4.2	1.9	-6.6	1.1	-8.4
April	10.2	0.0	11.5	1.9	8.8	0.5	10.6	0.9
May	17.4	5.3	21.1	8.0	18.3	5.5	17.5	5.3
June	23.2	11.0	25.7	11.7	20.8	9.4	21.9	11.3
July	25.5	12.7	24.9	13.2	21.5	12.0	25.5	15.0
August	24.6	11.6	25.0	14.0	21.7	11.6	25.7	13.2
September	20.2	8.2	19.7	7.8	19.7	9.1	16.7	7.6
October	13.8	3.1	13.9	5.3	11.4	1.6	11.3	2.4
November	5.5	-1.8	4.6	-2.3	4.1	-1.4	4.6	-1.9
December	-1.6	-8.7	-0.1	-7.9	0.0	-5.5	-1.1	-8.7

Figure 2.2: Mean monthly maximum and minimum temperatures ( $^{\circ}\text{C}$ ) for the 1951-1980 period and the three years of this study.



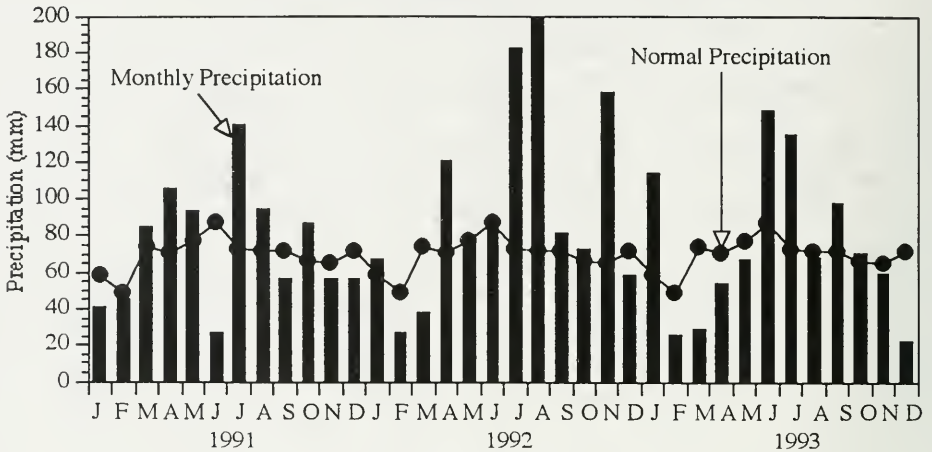
#### 2.2.2.2 Precipitation

The monthly precipitation totals and monthly normals for the 1951-1980 period are given in Table 2.2 and plotted in Figure 2.3. The precipitation total for 1991 was slightly higher than normal with the excess occurring in early and late summer (Figure 2.3). The precipitation total for 1992 was 40 % greater than the normal with most of the excess occurring during the months of April, July, August and November. The 1993 precipitation amount was slightly above normal with excess amounts in June and July and below normal amounts in the winter and early spring months.

Table 2.2: Monthly precipitation (mm) for the 1951-1980 period and for the three years of this study as recorded at the Elora Research Station.

Month	Precipitation (mm)			
	1951-80	1991	1992	1993
January	58.3	40.9	67.2	114.8
February	48.9	45.1	27.3	25.4
March	74.1	84.4	38.1	28.7
April	70.2	105.6	120.9	54.0
May	77.6	93.6	80.8	67.4
June	86.9	26.6	86.3	148.2
July	73.0	140.8	182.3	135.1
August	72.1	95.0	198.5	67.9
September	71.3	56.6	81.4	98.1
October	66.3	86.8	72.4	70.8
November	65.7	56.1	157.6	59.9
December	71.5	56.8	58.8	22.0
May-Oct.	447.2	499.4	701.7	587.5
Total	835.9	888.3	1171.6	892.3

Figure 2.3: Monthly precipitation (mm) for the 1951-1980 period and the three years of this study as recorded at the Elora Research Station.



#### 2.2.2.3 Evapotranspiration

A detailed water balance requires knowledge of the amount of water lost to the atmosphere through evaporation and transpiration. Potential evapotranspiration, PET, is the maximum amount of water that can be lost to the atmosphere according to the available energy at the soil surface when the supply of water in the soil is not limited. The water is lost either through evaporation from the soil surface and / or from plant transpiration. Since soil water can be limiting during the growing season, one must account for the decrease in potential evapotranspiration and estimate the actual evapotranspiration, AET. While there are many equations available to estimate PET, the ERS weather station calculates PET using the Priestley-Taylor equation (Priestley and Taylor, 1972) given as:

$$PET = \alpha \left( \frac{S}{S + P_{syc}} \right) (R_n - GO) \quad [2.1]$$

where  $\alpha$  is a coefficient which accounts for aerodynamic factors,  $S$  ( $\text{Pa } ^\circ\text{C}^{-1}$ ) is the slope of the saturation vapour pressure curve and  $P_{\text{psyc}}$  is the psychometric constant which is equal to  $66 \text{ Pa } ^\circ\text{C}^{-1}$  at  $20^\circ\text{C}$ ,  $R_n$  ( $\text{MJ m}^{-2}$ ) is net radiation and  $G_0$  ( $\text{MJ m}^{-2}$ ) is the soil heat flux. The soil water supply in southern Ontario is rarely limited during the growing season so that PET and AET can be considered approximately equal (Brown et al., 1968). The value of  $\alpha$ , in Eq. [2.1] is usually set to 1.26 for these conditions. In droughty summers, such as 1988, the value of  $\alpha$  should be reduced to reflect the limited supply of soil water. Table 2.3 gives the AET estimates for the three years of this experiment as reported by the ERS weather station and for the 1988 - 1992 period. Note that evapotranspiration estimates are considered to be negligible during January, February, November and December.

Table 2.3: Potential and actual evapotranspiration estimates (mm) for the Elora Research Station for the three years of this study.

Month	1988-92	1991	1992	1993
	PET	PET	PET	PET
January	-	-	-	-
February	-	-	-	-
March	21.2	22.9	19.5	21.3
April	49.3	46.0	45.7	49.0
May	84.8	87.8	94.3	86.1
June	107.7	132.5	106.0	106.0
July	114.8	128.8	100.3	128.5
August	95.0	106.5	83.1	105.5
September	58.8	66.1	59.3	45.9
October	24.3	25.9	25.3	32.3
November	-	-	-	-
December	-	-	-	-
Total	555.9	616.5	533.5	574.6

#### 2.2.2.4 Net Water Surplus / Deficit

The net water surplus or deficit is simply the difference between precipitation and PET. In a typical year, there is a net surplus from mid September through to mid April and a net deficit throughout the summer months (Figure 2.4). This pattern also reflects the annual leaching pattern of mobile soil chemicals such as  $\text{NO}_3^-$  - N.

Figure 2.4: Net water surplus and deficit for a typical year.

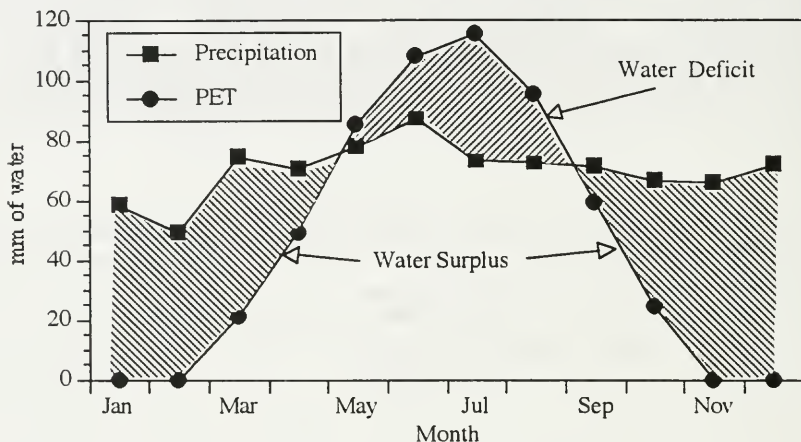
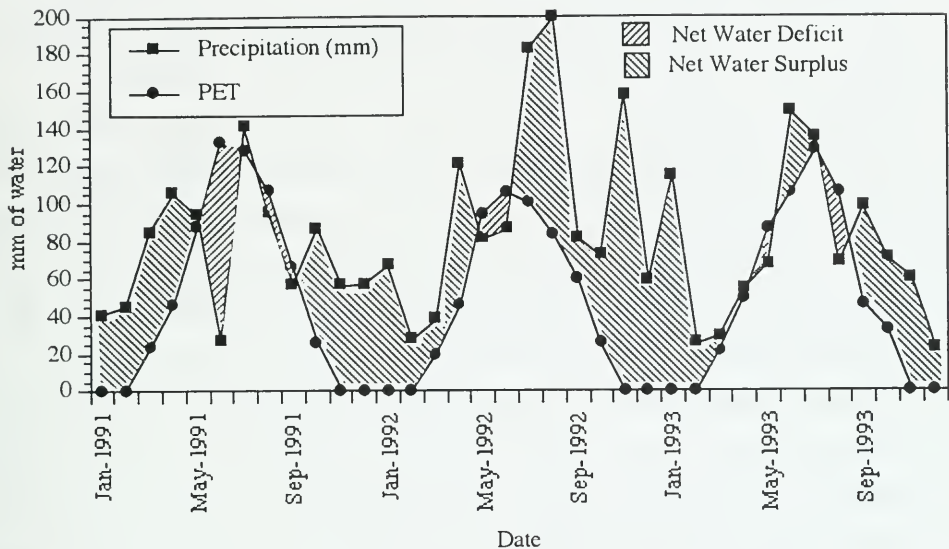


Figure 2.5 gives the net water deficits for the years of this study. The above average precipitation measured throughout this study (Table 2.2) is reflected in the small net water deficits. The net water surpluses were not shown for the sake of clarity. These net water surpluses do not necessarily represent the exact magnitude of water draining from the soil profile as changes in soil water storage have not been accounted for. These changes will be presented in chapter 3 and will be used in conjunction with the  $\text{Cl}^-$  and  $\text{NO}_3^-$  - N leaching measurements to calculate total mass loadings out of the root zone.

Figure 2.5: Net water deficits / surpluses for the length of this study.



## 2.3 Experimental Design

### 2.3.1 Plot Design

A plot size of 9 x 9 meters was chosen to accommodate agronomic and soil N transport aspects of the project. The experiment was laid out as a three factor randomized complete block design (Figure 2.6). The factors with the number of levels in parentheses are,

1. Nitrogen Fertilizer Source (3)  
NH<sub>4</sub>NO<sub>3</sub>, Liquid Dairy Cattle Manure, Solid Beef Cattle Manure
2. Rate of Nitrogen Application (3)  
0.5x, 1x and 1.5x the recommended rate
3. Time of Application (2)  
Spring and Fall

In addition, a control treatment of no fertilizer or manure application was used. This gave a total of 19 treatments in each of the four blocks giving a total of 76 plots (Figure 2.6).

### 2.3.2 Nitrogen Application Rates

Recommended rates were determined based on the spring soil nitrogen test. The amount of soil nitrate to the 60 cm depth was  $23 \text{ kg N ha}^{-1}$  in the spring of 1991. Based on soil test calibration data and a fertilizer N / corn grain price ratio of 5, a fertilizer application rate of  $170 \text{ kg N ha}^{-1}$  was used (Kachanoski and Beauchamp, 1991). Ammoniacal-N content of manure is the primary form of nitrogen available to the plant in the year of application. Manure application rates were based on average ammoniacal-N concentrations. The ammoniacal-N content of manure will vary according to type of animal, method of collection and duration of storage. Liquid dairy cattle manure application rates of 150, 300 and  $450 \text{ kg total N ha}^{-1}$  were applied based on average ammoniacal-N content. Solid beef manure generally has a lower percentage of its total nitrogen in the ammoniacal form and thus less of the total nitrogen is available for plant uptake in the season of application. For this reason, solid manure is generally applied at higher rates than liquid manures. Solid dairy beef cattle manure was applied at a rate of 200, 400 and  $600 \text{ kg total N ha}^{-1}$ . The high rate was chosen to be in excess of what most producers would normally apply. In the spring of 1991,  $\text{NH}_4\text{NO}_3$  was applied at the recommended rate ( $170 \text{ kg N ha}^{-1}$ ) to all fall treatments in order to maintain normal agricultural practices. Table 2.4 gives the chemical characteristics and recommended rate of manure applications that were used throughout the study. The experimental methods used to measure the various parameters and processes will be outlined in the appropriate section. Timetables of agronomic events will be presented in the agronomy section (Chapter 4).

## 2.4 Methodology

### 2.4.1 Soil Water Content

Soil water content,  $\theta_v$ , was nondestructively measured on a weekly basis at five different locations (marked SWC on Figure 2.6) except during the winter months.  $\theta_v$  was measured using time domain reflectometry (TDR) from the 0 - 40 cm (0 - 70 cm in 1991) and 0 - 80 cm depths (Topp et al., 1980). The mean  $\theta_v$  values at each depth are given for the various measurement dates



Table 2.4: Dry matter, N, P, K and C composition and recommended rate of application of the solid beef and liquid dairy cattle manure used in this study.

Manure Type and Time of Application	Dry Matter (% wet)	Total N (% wet)	$\text{NH}_4^+$ - N (mg N kg <sup>-1</sup> )	$\text{NO}_3^-$ - N (mg N kg <sup>-1</sup> )	P (% wet)	K (% wet)	Total C (% dry)	Inorganic C (% dry)	Recommended Application Rate (kg ha <sup>-1</sup> )
<b>Solid Beef</b>									
Spring 1991	nd	.455	1038	nd**	nd	nd	nd	nd	88000
Fall 1991	18.70	.405	323	nd	nd	nd	nd	nd	99000
Spring 1992	20.20	.567	848	nd	nd	nd	nd	nd	71000
Fall 1992	17.75	.350	747	nd	nd	nd	nd	nd	114000
Spring 1993	17.08	.335	37	4.07	.090	.315	46.470	.177	117647
<b>Liquid Dairy</b>									
Spring 1991	nd	.27	1350	nd	nd	nd	nd	nd	(L ha <sup>-1</sup> )
Fall 1991	6.15	.255	1060	nd	nd	nd	nd	nd	111000
Spring 1992	6.75	.256	1064	nd	nd	nd	nd	nd	118000
Fall 1992	3.18	.167	1096	nd	nd	nd	nd	nd	117000
Spring 1993	7.14	.322	1095	2.00	.070	.170	45.53	.143	180000
									93827

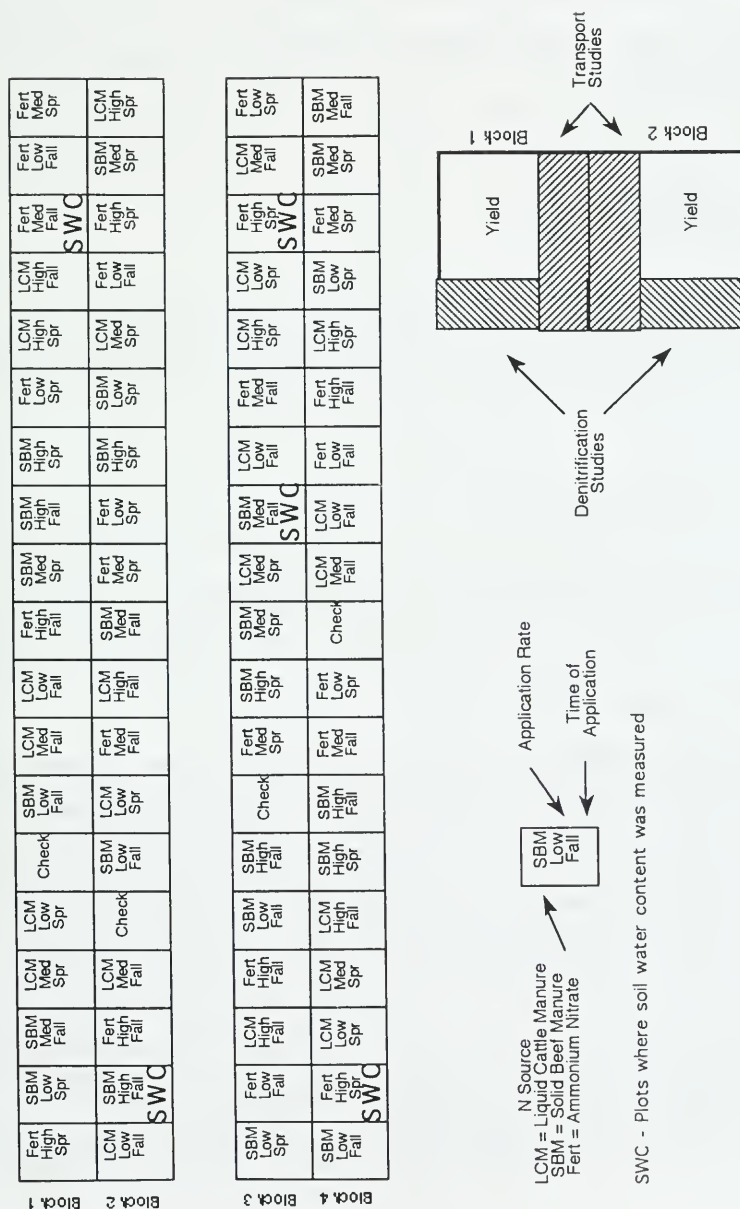
\* % wet - % on a wet matter basis

% dry - % on a dry matter basis

\*\* nd - not done



Figure 2.6: Plot layout of nitrate contamination of groundwater project at the Elora Research Station.



in Appendix 1. Wave guides were constructed from 2 mm diameter stainless steel rods. The TDR cable tester unit produces an apparent probe length based on an assumed dielectric, K. The true soil water content can be determined by calculating the ratio of the apparent length to the true probe length. K is calculated by:

$$K = \left( \left( \frac{\text{TDR Reading}}{\text{Probe Length}} \right) * \frac{MC}{V_p} \right)^2 \quad [2.2]$$

where MC is the TDR machine constant which was determined to be 0.9893 for this study and  $V_p$  is the propagation velocity equal to 0.99. The soil water content is related to K by the following formula:

$$\theta_v = a + b \cdot K + c \cdot K^2 + d \cdot K^3 \quad [2.3]$$

where a, b, c and d are empirical constants with values  $a=-0.053$ ,  $b=0.0292$ ,  $c=-5.5 \cdot 10^{-4}$ ,  $d=4.3 \cdot 10^{-6}$ .

#### 2.4.2 Soil Solution Samples of $\text{NO}_3^-$ and $\text{NH}_4^+$

Two solution samplers were installed, at the 80 cm depth, on each plot to measure the soil solution concentrations of  $\text{NO}_3^-$  and  $\text{NH}_4^+$  leaving the root zone of the various treated plots. Solution samplers were constructed using porous ceramic cups (2.5 cm diameter, 5.0 cm long) attached to PVC tubing. By using vacuum manifolds, several solution samplers could be sampled at the same time and sampling each group of samplers required approximately 15 minutes. In 1991 and 1992, a portable manifold was used to simultaneously collect samples from groups of 10 solution samplers. In 1993, a permanent manifold was used to simultaneously collect samples from 20 solution samplers. The permanent manifold was favoured as sample collection time was reduced from 5 hours to 2 hours, sample volumes increased and samples were collected from over 90 % of

the samplers as compared with approximately 60 % of the samplers when the portable manifold was used.

Soil solution samples were kept frozen until they could be analysed. A Technicon TRAACS 800 autoanalyser and Technicon Industrial Methods #780-89T and #824-89T were used to determine the concentrations of  $\text{NO}_3^-$  - N and  $\text{NH}_4^+$  - N, respectively (Tel and Heseltine, 1990a).

#### 2.4.3 Mineral N

The extractable mineral N to a depth of 60 cm was monitored two weeks prior to planting and every two weeks after up until approximately the 6 leaf stage. Ten soil samples from the 0 - 15 cm, 15 - 30 cm and 30 - 60 cm depths per plot were collected at each sampling period using a standard 2.5 cm oakfield soil sampler. The ten samples at each depth were mixed together and approximately 15 g of wet soil was used to determine the gravimetric soil water content. In addition, approximately 25 g of wet soil was added to a flask with 50 mL of 0.5 M  $\text{K}_2\text{SO}_4$ . The slurry was shaken for one hour and filtered. The filtered solution was then analysed for  $\text{NO}_3^-$  - N and  $\text{NH}_4^+$  - N using similar methods as discussed in section 2.4.2. Identical sampling was also carried out to monitor the accumulation of mineral N in the fall of 1993.

#### 2.4.4 Total Soluble Nitrogen, Total Organic Carbon, Extractable Carbon and Extractable Nitrogen

The same samples that were analysed for mineral N were also analysed for total soluble nitrogen (TSN) and dissolved organic carbon (DOC). TSN was determined by U.V. digestion and colorimetric detection of a diazo complex formed by reaction with  $\text{NO}_2^-$  (Technicon Method #759-84I). DOC was determined by U.V. digestion and colorimetric detection of  $\text{CO}_2$  production (Technicon Method #455-76W/A).

Two mineral N sampling dates in 1991, one date in 1992 and one date in 1993 were used to estimate microbial biomass C and N by determining the chloroform ( $\text{CHCl}_3$ ) extractable N and extractable C. Extractable C ( $\text{C}_{\text{Ex}}$ ) is calculated according to the formula,

$$C_{Ex} = C_{Fum} - C \quad [2.4]$$

where  $C_{Fum}$  is the amount of DOC from a soil sample that has been fumigated with  $CHCl_3$  for 24 hours and  $C$  is the amount of DOC from the original 0.5 M  $K_2SO_4$  extraction. The release of organic N and C upon exposure to  $CHCl_3$  has been correlated to the microbial biomass C and N in a wide range of soils (Voroney et al., 1993). The amount of biomass C is calculated by dividing  $C_{Ex}$  by an empirically determined extraction factor,  $K_c$ , which accounts for the portion of the microbial C that is released by fumigation. Similar calculations can be done to calculate the amount of extractable N,  $N_{Ex}$ . The consistency of the extraction factors is unclear. Here we report the extractable C and extractable N leaving the calculation of biomass C and N to the reader.

#### 2.4.5 Denitrification

Various detailed measurements, designed to characterize aspects of the denitrification process, were carried out in the spring of 1993. These measurement included denitrifying enzyme activity (DEA),  $N_2O$  production,  $CO_2$  production and denitrification rate. Some of these measurements were carried out on all of the plots while others were performed on selected plots only. A description of analytical methods for studying denitrification has been discussed in detail by Beauchamp and Bergstrom (1993).

##### 2.4.5.1 Denitrifying Enzyme Activity

The purpose of the DEA measurements was to assess the potential for denitrification under the various treatments. Ten soil samples were collected from the 0 - 15 cm, 15 - 30 cm and 30 - 60 cm depths on each plot on June 14, 1993. The ten samples at each depth for each plot were combined and brought back to the laboratory for analysis. Approximately 25 g of wet soil was added to a 100 mL amber flask. 25 mL of a buffer solution containing 50 mM  $H_2KPO_4$ , 10 mM  $NO_3^-$  - N and 10 mM glucose - C was added to the flask. Anaerobic conditions were attained by flushing the head space with He. After 15 minutes of flushing, 8 mL of the head space was

removed and replaced with 8 mL of  $C_2H_2$  to prevent the formation of  $N_2$ . The flasks were then placed on a mechanical shaker and samples were withdrawn after 15 minutes and 1 hour of shaking. The samples were analysed for  $N_2O$  on a gas chromatograph using an electron capture detector.

#### 2.4.5.2 $N_2O$ Production, $CO_2$ Production and Denitrification Rate

The  $N_2O$  production measurement quantifies the combined amount of N loss from nitrification and a portion of that lost via denitrification at the time of sampling. The  $CO_2$  production measurement quantifies the amount of C that is being respired by the microbial biomass at the time of sampling. The denitrification rate measurement quantifies the amount of N loss from the denitrification process at the time of sampling. These three measurements were made at various times following the manure applications in the spring of 1993.

At each sampling time, soil cores (4.5 cm diameter, 5 cm length) were taken from the 2.5 - 7.5 cm depth from the plots that received high rates of manure or fertilizer applications in the spring. The control plots were also sampled at the same time. The soil cores were placed in 250 mL jars and sealed. Each jar had an air sample withdrawn approximately 2.5 hours later. These samples were analysed for  $N_2O$  and  $CO_2$  production using an electron capture detector and a thermal conductivity meter, respectively. The jars were then opened and aired out for 15 minutes. After sealing the jars again, 10 mL of head space was evacuated and replaced with 10 mL of  $C_2H_2$  to prevent accumulation of  $N_2$ . After approximately 15 hours, the jars were sampled for  $N_2O$ .

#### 2.4.6 Plant Analyses

##### 2.4.6.1 Grain and Stover Yield

Four 3 m long rows in each plot were hand harvested for stover and grain yield calculations just prior to the crop being taken off for silage. The total number of cobs and total weight was recorded for each plot. A 10 cob subsample was taken and dried to obtain the dry grain yield. Similarly, a subsample of the stover from each plot was taken and dried. Grain and stover yields

are all reported on a dry weight basis. Note that the plots that received fertilizer and manures in the fall of 1991 were not hand harvested for grain yield as all of these plots had been fertilized with synthetic fertilizer in the spring. This ensured continuation of normal agricultural practices until the fall treatments could be applied. Also note that the stover was not harvested in the fall of 1991.

#### 2.4.6.2 N Concentration in Grain and Stover

The concentration of N in each of the stover and grain was also measured at the end of the 1992 and 1993 growing seasons. Only the grain was analysed for N content in 1991. The dried grain and stover was ground and a subsample of each was analysed for total N by the University of Guelph Analytical Services Laboratory using a slightly modified digestion method (Thomas et al., 1967). Digestion solutions were then analysed on a Technicon autoanalyser.

#### 2.4.6.3 Crop Height and Leaf Area Index

The leaf area index is the area of leaves divided by the ground area below the leaves and is required to estimate transpiration. A one meter transect at the top of blocks 3 and 4 was randomly chosen on a weekly basis, throughout the 1993 growing season, to have the leaves on all the plants within the transect removed. All of the leaves were cleaned and brought back to the University of Guelph. The leaves were passed through an automatic area meter (Hyashi Denko Co. Ltd., Japan) and the total area was measured. Since the plant spacing varies somewhat in the field, the total transect leaf area was corrected for a plant density of 64000 plants ha<sup>-1</sup> based on the number of plants in the transect.

Five plants were randomly selected at the top of blocks 3 and 4 throughout the 1993 growing season to have their height and number of leaves measured. Crop height was measured as the distance from the ground to the highest part of the plant.



#### 2.4.7 Tracer Experiments

Two different types of tracer experiments were carried out in 1992 and 1993. These tracer experiments involved applying a conservative tracer to the ground surface and taking soil cores at various depths throughout the growing season. A conservative tracer is one that does not react with soil particles or soil organic matter and moves freely with percolating water.  $\text{Cl}^-$ , applied as KCl, was used in the experiments reported here. However, it has been shown that  $\text{Cl}^-$  is taken up by corn plants so that it is not a truly conservative tracer (Younie, 1993). These tracer experiments provide information regarding the amount of a chemical that can be lost from the soil profile given a specific amount of net drainage of water through the profile.

In the spring of 1992,  $100 \text{ g m}^{-2}$  of  $\text{Cl}^-$  ( $210.3 \text{ g m}^{-2}$  KCl) was applied to a  $4 \text{ m}^2$  subplot of the plots that received low rates of fertilizer in the spring. These plots were sampled twice during the growing season to a depth of 1 m in 0.10 m increments. The soil was brought back to the laboratory where approximately 15 g of wet soil was used for a soil water content determination. Approximately 25 g of wet soil was placed in a flask to which 50 mL of distilled water was added. The mixture was shaken for 1 hour and then filtered. The solution was analysed for Cl using a Technicon TRAACS 800 analyzer (Technicon Industrial Method #834-89T) (Tel and Heseltine, 1990b). Three plants from each subplot were hand harvested and dried for chemical analysis.  $\text{Cl}^-$  uptake was determined by shaking 2.5 g of dry plant material in 50 mL of distilled water for one hour. The solution was then analysed for  $\text{Cl}^-$  using the same methodology discussed above.

The same amount of  $\text{Cl}^-$  was applied on December 8, 1992 to  $4 \text{ m}^2$  subplot of the plots that received low rates of fertilizer in the fall. These plots were sampled several times throughout the 1993 growing season in the same way as in 1992. In addition, a detailed tracer experiment was performed in 1993 in the area at the top of blocks 1 and 2 (Figure 2.4). A  $60 \text{ m}^2$  area was chosen to have  $100 \text{ g m}^{-2}$  of  $\text{Cl}^-$  applied to it on June 2, 1993. At various times throughout the 1993 growing season, 3.75 m transects were randomly chosen for soil sampling. Five row positions and five interrow positions were sampled to a depth of 0.80 m in 0.05 m increments at each position. The soil at each depth was combined for each position and brought back to the laboratory where it

was analysed for  $\text{Cl}^-$  by the same method as discussed above. Five plants were randomly harvested at the end of the growing season (August 24, 1993) and  $\text{Cl}^-$  uptake was measured by the same method as discussed above. In addition, soil water content and impedance was measured in 0.05 m increments to a depth of 0.80 m using TDR.

## Chapter 3 Detailed Soil Properties and Hydrology

### 3.1 Physical and Chemical Soil Properties

As mentioned previously, the soil at this site is a Conestogo silt loam which is the imperfectly drained member of the Woolwich catena. It is closely associated with the London loam of the Guelph catena. This soil is classified as a Gleyed Melanic Brunisol and has Ap, Bmgj and Ckg horizons (Presant and Wicklund, 1971).

Twelve locations were randomly chosen to have soil cores (5 cm length x 2.5 cm diam.) taken from the 20 cm depth to the 100 cm depth in 10 cm increments to determine bulk density ( $\text{g cm}^{-3}$ ), soil water content versus suction relationships and saturated hydraulic conductivity ( $\text{cm day}^{-1}$ ). These measurements were made according to standard laboratory techniques (Canadian Society of Soil Science, 1981). Soil textural data, bulk density and saturated hydraulic conductivity data were also available from other sources (van Wesenbeeck, 1987; Lee, 1984). Table 3.1 gives the physical and chemical properties, of the Conestogo silt loam, as measured from the soil cores and as reported in the previously mentioned reports.

Table 3.1: Physical and chemical properties of the Conestogo silt loam (Presant and Wicklund, 1971).

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	pH	O.M.* (%)	Ksat** ( $\text{cm day}^{-1}$ )	$\rho_b$ *** ( $\text{g cm}^{-3}$ )
Ap	0 - 25	25.8	54.7	18.3	7.0	5.6	57.3	1.40
Bmgj1	26 - 35	36.7	38.3	25.0	7.3	0.9	41.5	1.59
Bmgj2	36 - 50	37.0	47.0	16.0	7.6	0.6	32.1	1.87
Ckg	51 +	37.0	47.0	16.0	7.6	0.0	18.3	1.95

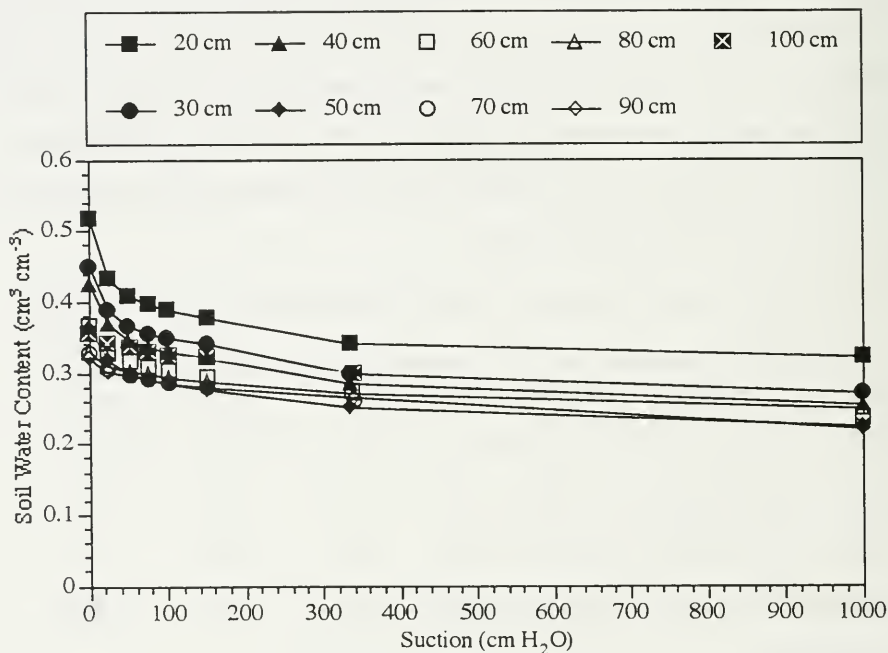
\* Organic matter.

\*\* Saturated hydraulic conductivity.

\*\*\* Bulk density

Soil water content versus suction relationships provide information that is necessary to quantify the water holding capacity of a soil. For example, these relationships can be used to estimate the amount of water available to plants before wilting occurs and the soil water content, above which, drainage due to gravity occurs. These relationships are required by most soil water models to predict changes in soil water content over the growing season. The soil water models use this information to fit one of several equations developed to describe these relationships (Campbell, 1974; van Genuchten, 1980). Figure 3.1 gives the soil water content versus suction curves, at each depth, for the mean of the twelve soil core sampling locations.

Figure 3.1: Soil water content versus suction relationships for the mean of the twelve soil core sampling locations.



## 3.2 Site Hydrology

### 3.2.1 Annual Water Balance

To calculate the total mass per area of N lost to the groundwater based on measured concentrations of  $\text{NO}_3^-$  - N ( $\text{mg N L}^{-1}$ ), the net drainage flux ( $\text{cm}^3 \text{ cm}^{-2} \text{ day}^{-1}$ ) must be estimated. However, assuming that there are negligible differences in the water regime between treatments, relative  $\text{NO}_3^-$  leaching amounts can be inferred from soil water solution concentrations of  $\text{NO}_3^-$  and  $\text{NH}_4^+$ . The use of a water balance can be used to give an estimate of mean annual net drainage at this site. A water balance is calculated by quantifying the inputs and outputs of water into and out of the soil profile. The water balance can be written as:

$$\text{Net Drainage} = \text{Precipitation} - \text{Runoff} - \text{Actual Evapotranspiration} + \Delta \text{Storage} \quad [3.1]$$

where  $\Delta S$  is storage at time 1 minus storage at time 2 and net drainage is positive downwards.

Precipitation and actual evapotranspiration were discussed in sections 2.2 and 2.3, respectively. Runoff occurs when the precipitation intensity exceeds the soil's ability to absorb it. Runoff is difficult to measure but can be expected to occur at this site in early spring and late fall. In addition, runoff may also occur to some extent during brief and intense summer thunderstorms. Coulson (1967) estimated that mean annual streamflow (drainage + runoff) was 279 mm for the area of southern Ontario where this study was performed. This value is in good agreement with the 1951-1980 normal precipitation minus evapotranspiration values given in Chapter 2. Witherspoon and Ayers (1958) measured runoff amounts of approximately 76 mm in each of 1953 and 1954 on a small agricultural watershed near the site of the study reported here. These years had approximately normal amounts of precipitation and they found that 80 % of the runoff occurred during the spring thaw period (March - April). Coote (1975) examined runoff amounts from different feedlots in southern Ontario, in 1973, and measured 138 mm of runoff from a feedlot with a soil surface. Singh (1970) measured runoff amounts from two small agricultural watersheds near Guelph in 1967 and 1968. He measured 53 mm and 31 mm of runoff in the April to September

periods of 1967 and 1968, respectively. These values underestimate annual runoff as they do not account for all of the spring runoff. Considering the above information, it seems likely that the study site has approximately 100 mm of surface runoff per year.

Storage is the amount of water stored in the profile at any given time. When considered on an annual basis, the change in storage is small and can often be considered negligible. The change in storage can be calculated as the difference in the total amount of water in the soil profile at the beginning of the year and the amount of water at the end of the year. Table 3.2 gives the difference between the measured amounts of water in the top 80 cm early and late in the year at this site. The change in storage for 1993 should most likely be less negative as the 'early' soil water content reading was taken after much of the spring drainage had taken place.

Table 3.2: Measured differences between the amount of water in the soil profile early and late in the year for the three years of this study.

Year	Amount of Water		
		(cm)	
	Early	Late	$\Delta$ Storage
1991	na	24.8	na*
1992	28.6	26.9	1.7
1993	24.3	30.3	-6.0

\* not available

Table 3.3 gives the components of the water balance for the three years of this study as well as the 1951-1980 normals. Note that the 1951-1980 AET values are the mean of the 1988 -1992 years. We will consider the change in storage to be negligible on an annual basis.

Table 3.3: Water balance components for the three years of this study and the 1951-1980 normals.

Year	Precipitation (mm)	AET (mm)	Runoff (mm)	$\Delta$ Storage (mm)	Net Drainage (mm)
1951-1980	835.9	555.9	100	0	180.0
1991	888.3	616.5	100	0	171.8
1992	1171.6	533.5	100	0	538.1
1993	892.3	574.6	100	0	217.7

The amounts of net drainage for the 1951 - 1980 period and 1992 year agree with the value of 160 mm given by Goss et al. (1992). The amount of runoff for 1992 is most likely underestimated considering the large amount of precipitation that the site received. Figure 2.2 indicated that the months of April, July, August and November received much higher than normal amounts of precipitation. It is likely that much of the April and November rainfall amounts can be considered as runoff and some of the July and August. Notwithstanding this, the net drainage for 1992 would have been much higher than normal.

### 3.2.2 Measured Water Balance

In addition to the annual water balance and estimate of the net drainage or net surplus of water, the net surplus / deficit of water in the soil profile can be calculated during the time when the soil water content was measured. This data will be required in Chapter 5 to analyse the tracer experiments that were performed during this project and to make environmental assessments of the various N sources.

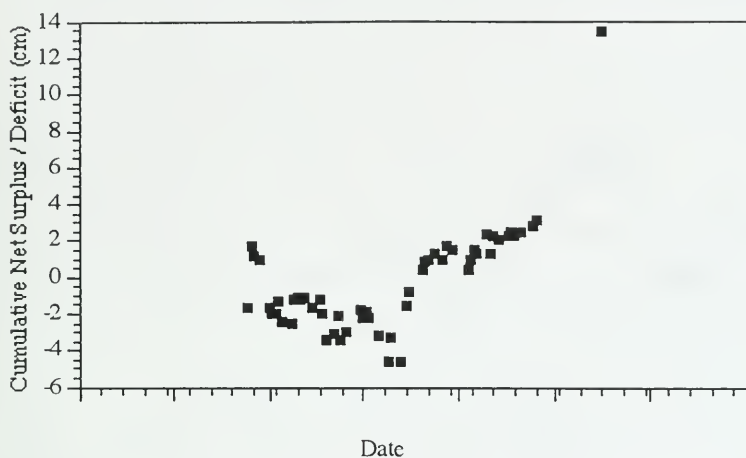
The water balance quantifies the inputs and outputs from the soil profile as indicated by Eq. [3.1]. It is reasonable to assume that runoff is negligible during the growing season and AET can be approximated with the Priestley - Taylor equation (Priestley and Taylor, 1972), Eq. [2.1], using hourly meteorological data (Appendix 2). In addition, we also make the assumption that water movement into the soil profile from the water table is negligible. Monitoring the soil water content



to a specific depth at each time of interest will give the storage for each particular time. The change in storage between the two particular times ( $\Delta S$ ) can be calculated, precipitation and evapotranspiration, in the time period, is known and Eq. [3.1] can be used to calculate the net surplus or deficit. The net surplus / deficit for 1992 and 1993 growing seasons is given in Appendix 4 as calculated by the method discussed above. Net surplus / deficit is only given for those days on which the soil water content was measured for each growing season (Appendix 4). Net surplus / deficit, as presented here is on a cumulative basis since the first day of each year when the soil water content was measured. Net surplus / deficit can also be calculated on an incremental basis between each soil water measurement period. The data calculated on an incremental basis are also given in Appendix 4.

Figure 3.2 gives the 1992 cumulative net surplus / deficit past the 80 cm depth. The 1993 calculated net surplus / deficit was measured over a longer time period so that the fall leaching period could be characterized. As a result, measurements were made up until the freeze-up near the middle of December, 1993. Figures 3.3 and 3.4 give the calculated 1993 cumulative net surplus / deficit past the 40 cm and 80 cm depths, respectively. These figures are presented here and will be discussed and presented again in Chapter 5.

Figure 3.2: 1992 cumulative net surplus / deficit past the 80 cm depth.



The pattern of net surplus / deficit in 1992 was consistent with the amount and distribution of precipitation (Figure 2.3). The deficit became a surplus midway through July and remained that way as July and August precipitation totals were more than double the normal amounts. A surplus during the growing season meant that plant available N was being removed from the root zone which will be shown to influence the N supplying efficiency of the various N sources (Chapter 4).

Figure 3.3: 1993 cumulative net surplus / deficit past the 40 cm depth.

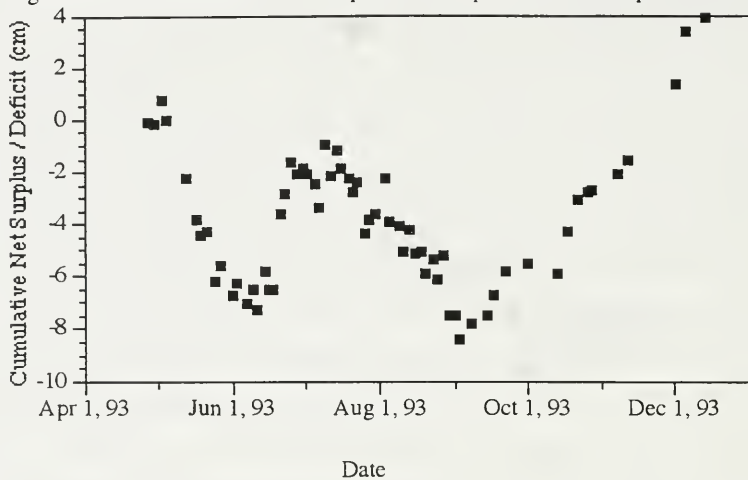
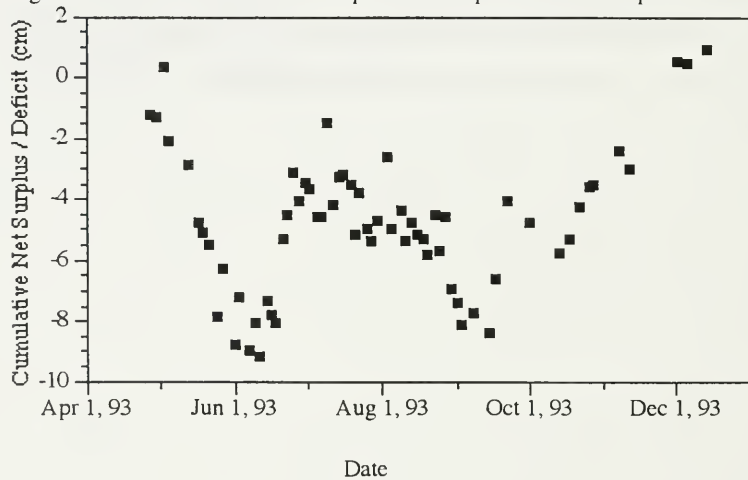


Figure 3.4: 1993 cumulative net surplus / deficit past the 80 cm depth.



Figures 3.3 and 3.4 indicate similar patterns in net surplus / deficit past the 40 cm and 80 cm depths. Unlike in 1992, a deficit remained until mid to late November when the soil profile had become recharged and drainage could once again occur. The approximately normal precipitation amounts in the fall of 1993 should provide a rough value for net surplus in a "typical" year. Unfortunately the spring drainage component was not well monitored.

Table 3.5 summarizes the cumulative net surplus / deficit past the 80 cm depth for the 1992 and 1993 growing seasons (April - October). Net surplus / deficit is not given for 1991 as only limited soil water content measurements were made during the growing season (Figure 3.5).

Table 3.4: Cumulative net surplus / deficit in the 80 cm depth for the 1992 and 1993 growing seasons as calculated by the water balance method.

Year	Net Surplus / Deficit (cm)
1992	13.31
1993	-3.58

Again, the above average summer precipitation is evident in 1992. The 1993 values are consistent with the normal net surplus / deficit conditions (Figure 2.4).

### 3.2.2 Soil Water Content

As discussed in chapter 2, soil water content,  $\theta_v$ , was nondestructively measured throughout the length of the experiment at five different locations except during the winter months.  $\theta_v$  was measured using time domain reflectometry (TDR) from the 0 - 40 cm (0 - 70 cm in 1991) and 0 - 80 cm depths (Topp et al., 1980). The mean  $\theta_v$  values at each depth are given for the various measurement dates in Appendix 1. The computer file of individual measurements is on the diskette at the back of this report. Figures 3.5 through 3.7 give the temporal variation of  $\theta_v$ , from the 0 - 40 cm (0 - 70 cm in 1991) and 0 - 80 cm depths for 1991, 1992 and 1993, respectively.

Figure 3.5: Soil water content ( $\text{cm}^3 \text{cm}^{-3}$ ) from the 0 - 70 and 0 - 80 cm depths in 1991.

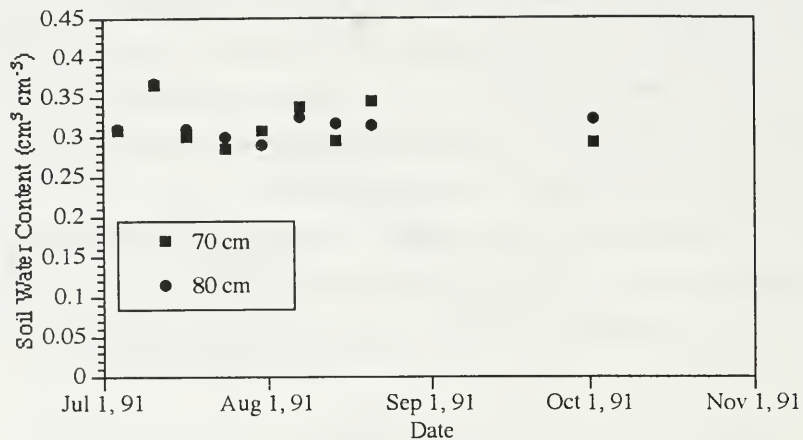


Figure 3.6: Soil water content ( $\text{cm}^3 \text{cm}^{-3}$ ) from the 0 - 40 and 0 - 80 cm depths in 1992.

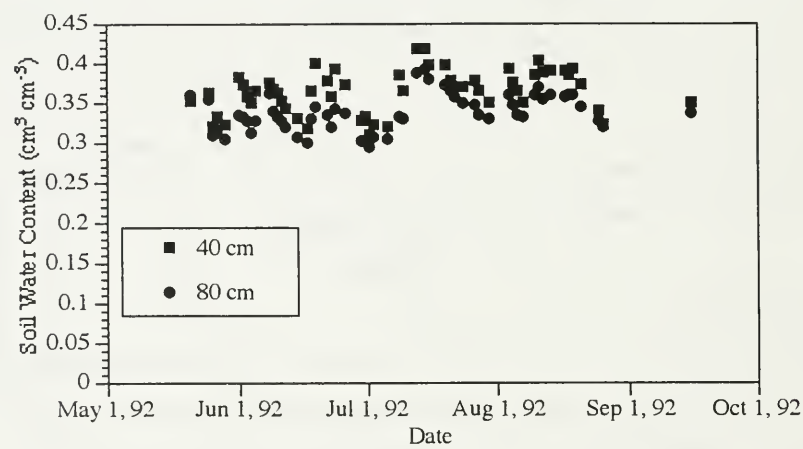
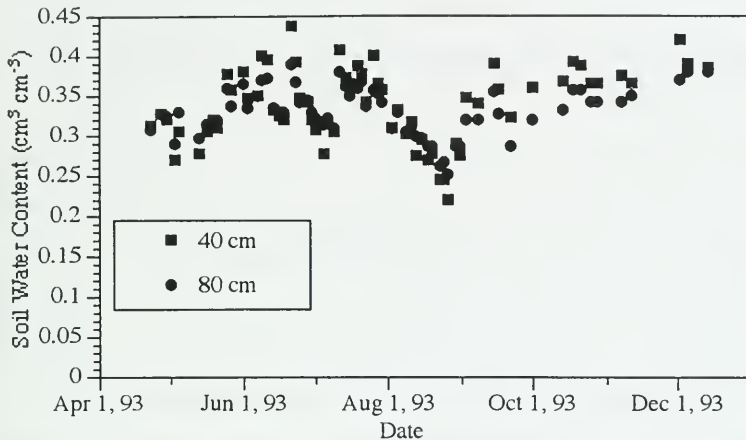


Figure 3.7: Soil water content ( $\text{cm}^3 \text{cm}^{-3}$ ) from the 0 - 40 and 0 - 80 cm depths in 1993.



All three years received approximately normal or above normal amounts of precipitation (Figure 2.3, Table 2.2). As a result, soil water contents remained approximately  $0.30 \text{ cm}^3 \text{cm}^{-3}$  or higher, except for a few brief periods in 1993. This allowed solution samplers to yield sufficient samples. In addition, AET could be considered to be approximately equal to PET and the three corn crops were not put under any serious water stress.

### 3.2.3 Soil Water Models

The water balance method of calculating mean annual net surplus / deficit gives an approximate value which can be used for rough comparisons, between sites, of the potential for chemical leaching. The net deficit / surplus in the root zone can also be obtained from soil water models such as the Leaching Estimation and Chemical Model (LEACHM; Wagenet and Hutson, 1989) and the Simulation of Field Water Use and Crop Yield (SWACROP; Belmans et al., 1983; Feddes et al., 1978). These models can be used to provide more accurate estimates, relative to the water balance method, of the drainage flux providing they accurately estimate the measured soil water contents. The LEACHM model was chosen to simulate the soil water content during the

1991, 1992 and 1993 growing seasons. In addition, LEACHM also predicted the net drainage flux out of the root zone on a daily basis. The net drainage data was used in conjunction with the solution sampler data and the mineral N soil samples to estimate total mass loadings of  $\text{NO}_3^-$  - N out of the root zone (Chapter 5).

A computer model, based on Eq. [2.1] was written to calculate evapotranspiration at various times of the growing season and at various stages of crop growth. The model and its description are given in Appendix 2. The measured meteorological data were used in conjunction with the evapotranspiration model and LEACHM to simulate the soil water content throughout the growing season (April 1 - October 31). The 1992 input file for the LEACHM model is given in Appendix 3. The model was calibrated with the 1992 0 - 80 cm depth measured soil water contents by changing soil parameters such as the bulk densities and textures. Figures 3.8 and 3.9 give the 1991 measured and LEACHM predicted soil water contents as a function of time for the 0 - 70 cm and 0 - 80 cm depths, respectively. Figures 3.10 and 3.11 give plots of predicted stored water versus the 1991 measured stored water for the 0 - 40 cm and 0 - 80 cm depths, respectively. Stored water is the amount of water in the soil profile at any one time and is calculated by multiplying the average soil water content by the depth of the soil profile. Similar figures are also given for the 1992 and 1993 0 - 40 cm and 0 - 80 cm depths (Figures 3.12 through 3.19). All of these figures show some discrepancies between the measured and predicted values. The initial rise in the predicted soil water contents is due to the low initial soil water contents in the input file. LEACHM is sensitive to the initial conditions of the soil profile and it was necessary to slightly decrease the initial soil water contents for the model to run. However, remembering that the model is a mechanistic one which is trying to represent a natural system, the results are fairly good. This means that the predicted drainage fluxes may be a reasonable approximation of the actual fluxes.



Figure 3.8: Measured and LEACHM predicted soil water content during the 1991 growing season for the 0 - 70 cm depth.

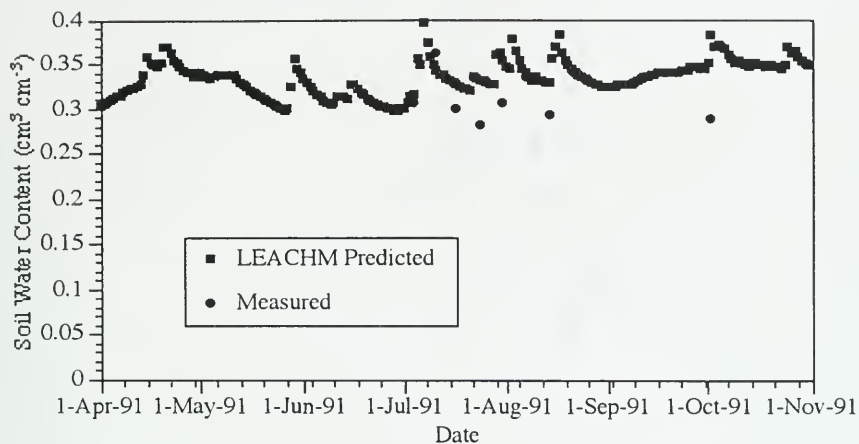


Figure 3.9: Measured and LEACHM predicted soil water content during the 1991 growing season for the 0 - 80 cm depth.

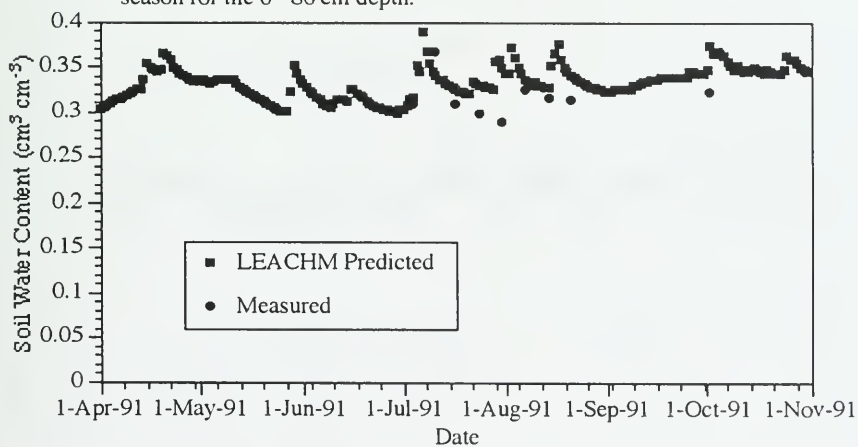


Figure 3.10: Measured versus LEACHM predicted stored soil water during the 1991 growing season for the 0 - 70 cm depth.

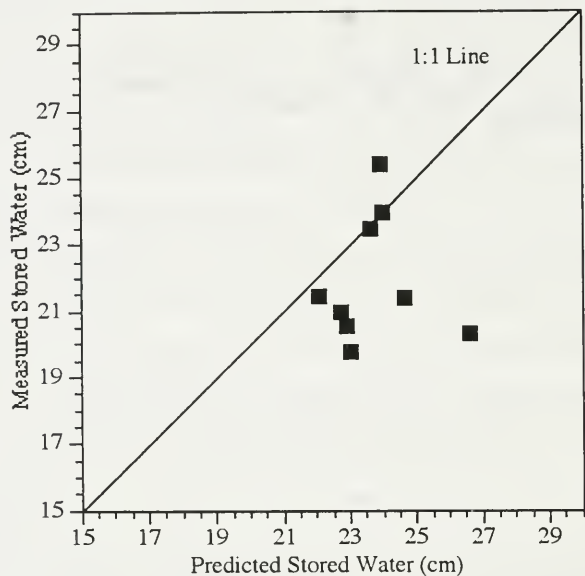


Figure 3.11: Measured versus LEACHM predicted stored soil water during the 1991 growing season for the 0 - 80 cm depth.

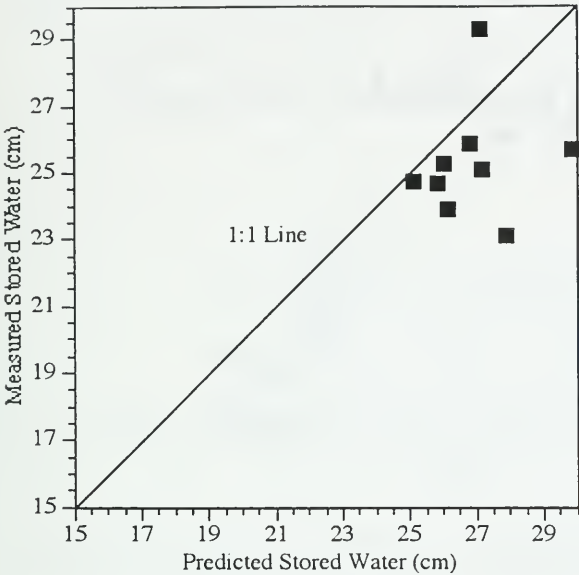


Figure 3.12: Measured and LEACHM predicted soil water content during the 1992 growing season for the 0 - 40 cm depth.

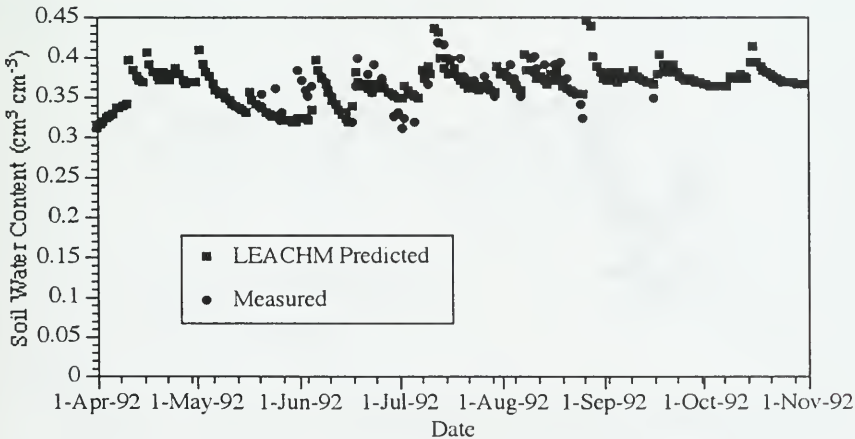


Figure 3.13: Measured and LEACHM predicted soil water content during the 1992 growing season for the 0 - 80 cm depth.

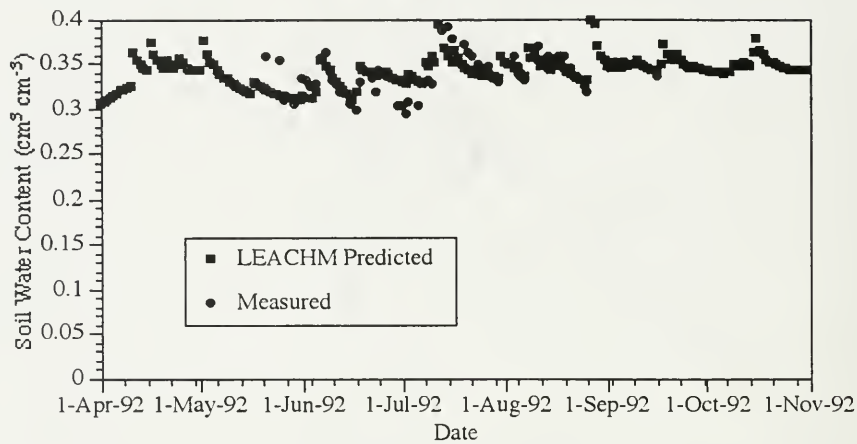


Figure 3.14: Measured versus LEACHM predicted stored soil water during the 1992 growing season for the 0 - 40 cm depth.

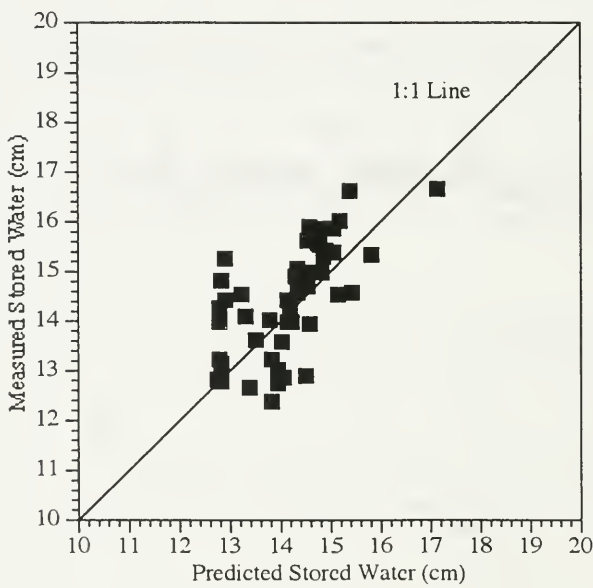


Figure 3.15: Measured versus LEACHM predicted stored soil water during the 1992 growing season for the 0 - 80 cm depth.

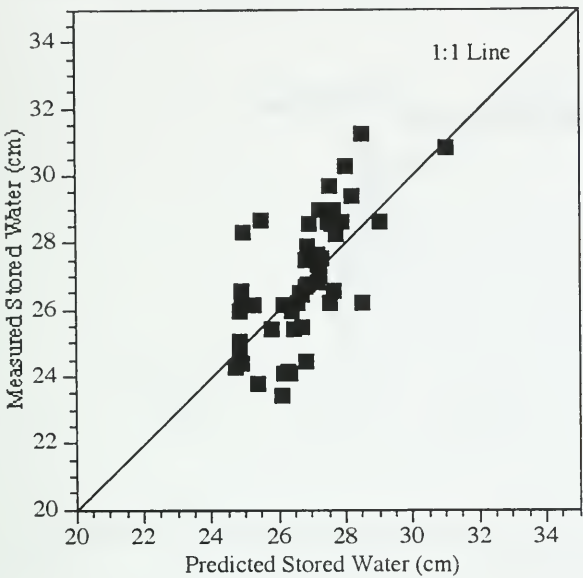


Figure 3.16: Measured and LEACHM predicted soil water content during the 1993 growing season for the 0 - 40 cm depth.

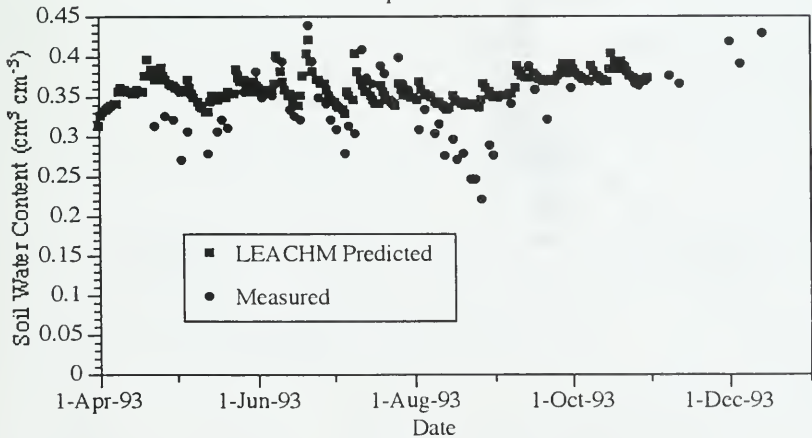


Figure 3.17: Measured and LEACHM predicted soil water content during the 1993 growing season for the 0 - 80 cm depth.

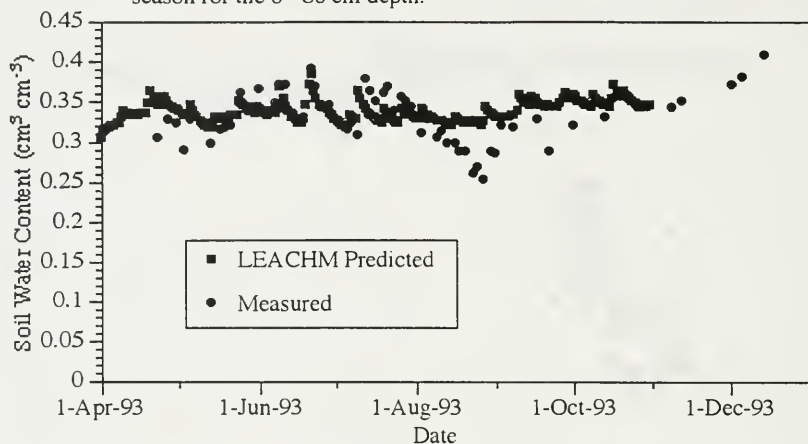


Figure 3.18: Measured versus LEACHM predicted stored soil water during the 1993 growing season for the 0 - 40 cm depth.

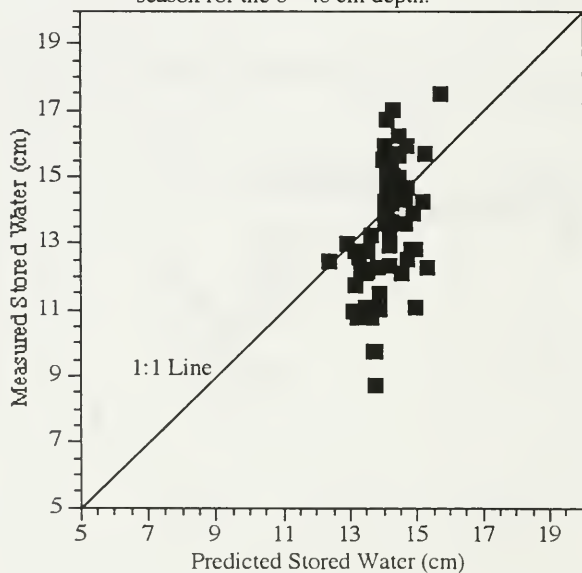
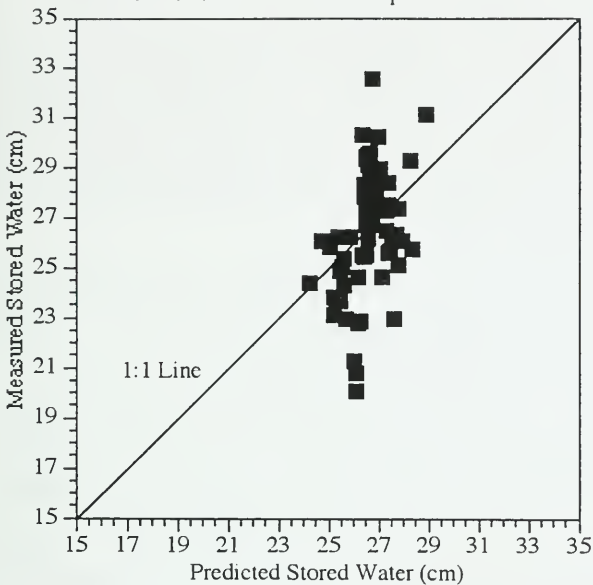


Figure 3.19: Measured versus LEACHM predicted stored soil water during the 1993 growing season for the 0 - 80 cm depth.



The flux of water draining past the 80 cm depth was also predicted by LEACHM (Table 3.4).

These values have been adjusted for the initial increase in soil water content that was observed in Figures 3.8, 3.9, 3.12, 3.13, 3.16 and 3.17. This extra water was allocated to the drainage flux since the soil profile is draining at this time of year (April).

Table 3.5: LEACHM predicted cumulative drainage flux past the 80 cm depth for the 1991, 1992 and 1993 April 1 - October 31 periods.

Year	Cumulative Drainage Flux (mm)
1991	-78.8
1992	323.3
1993	-14.9



The negative drainage flux in 1991 indicates that the loss of water through the top of the soil profile was estimated to be more than the water inputs for that year. Precipitation for the months of April - October was approximately 11.4 mm greater than the PET for the same time period (Tables 2.2 and 2.3). Considering the accuracy of these values, this suggests that there should be very little net drainage occurring during these months in 1991. In addition, LEACHM predicted that there would have been approximately 50 mm of runoff in 1991 which may not have been the case. If the runoff was allocated to net drainage, the net drainage would reflect the approximately equal rainfall and evapotranspiration conditions of the 1991 growing season.

The large positive drainage flux predicted by LEACHM in 1992 is consistent with the large amount of rainfall received during this year (Table 2.2, Figure 2.3). The effect of this large amount of drainage is important with respect to N leaching and crop response (Chapters 4, 5). The LEACHM estimate for the same time period as was done for the net surplus / deficit calculations (May 21, 1992 to September 16, 1992) gave an estimate of 160.7 mm net surplus. This value is similar to the calculated value of 133.1 mm (Table 3.4). The 1993 growing season was characterized by precipitation amounts that were approximately equal to AET amounts and thus there was little net drainage predicted by LEACHM. This was consistent with the calculated net surplus / deficit value (Table 3.4) and will be shown to be consistent with the  $\text{Cl}^-$  leaching experiment and water balance calculations (Chapter 5).

## Chapter 4 Corn Crop Responses

### 4.1 Introduction

This chapter is divided up by year and will summarise the agronomic practices that were maintained throughout the three growing seasons of this experiment. In addition, annual grain yields, stover yields, grain N concentrations and stover N concentrations will be discussed. Prior to this experiment, the field used for this project was cropped to continuous corn for 10 - 15 years. In the spring of 1991 the plots were seeded to corn. The corn hybrid used throughout this experiment was Pioneer 3902 at a rate of 64000 plants  $\text{ha}^{-1}$ . This hybrid requires approximately 2650 corn heat units and 100 days to mature. At the time of planting for each year, 200  $\text{kg ha}^{-1}$  of P and K in the form of 0-20-20 was applied. N from manure and fertilizer was applied prior to planting each year and no starter N fertilizer was applied with the seed. As mentioned in Chapter 2, the fall application plots received 170  $\text{kg N ha}^{-1}$  as ammonium nitrate in the spring of 1991 so as to maintain regular agronomic practices. Therefore, the 1991 yield data are not interpreted with respect to time of N application.

Corn grain yields and grain N concentrations were measured in each of the three years and are given in Appendix 5. Stover yield and stover N concentrations were only measured in 1992 and 1993 (Appendix 5). Note that grain and stover yields are reported on a dry weight basis. Average dry grain yields for the Elora Research Station are approximately 8  $\text{t ha}^{-1}$  (J. Ferguson, Pers. Commun.). In addition to measurement of yield data, leaf area index (LAI), number of leaves and crop height were measured as a function of time throughout the 1993 growing season (Appendix 6).

## 4.2 1991 Results

### 4.2.1 Agronomic Events

Table 4.1 gives the significant management and crop development dates for the 1991 growing season. The 1991 crop was planted at double the normal plant density but was later thinned to a density of 64000 plants ha<sup>-1</sup>.

Table 4.1: Significant agronomic event dates for the 1991 growing season.

Date	Agronomic Event
May 13 - 15, 1991	Manures and fertilizer applied, plots ploughed
May 19, 1991	Pioneer 3902 corn planted @ 128000 plants ha <sup>-1</sup> (thinned later)
May 24, 1991	100% emergence
May 30, 1991	2-3 leaf stage
June 19, 1991	Banvel sprayed
July 3, 1991	9-10 leaf stage
October 1, 1991	Hand harvest for yield determination
October 7 - 9, 1991	Manures and fertilizer applied, plots ploughed

### 4.2.2 Grain and Stover Yields and N Concentration

The 1991 growing season was characterized by air temperatures that were slightly above normal (Table 2.1, Figure 2.2) and precipitation amounts that were slightly below normal (Table 2.2, Figure 2.3). The precipitation in the month of June was well below normal with July's precipitation being well above normal (Figure 2.3). These conditions resulted in yields that were above average for this region of southern Ontario. Table 4.2 gives the summary of F values from the ANOVA of the 1991 grain yield and grain N concentration. The experimental design and the treatments used in the ANOVA were explained in section 2.3.1.

Table 4.2: Summary of F values for the various treatments for the 1991 grain yield and grain N concentration.

Source of Variation	Grain Yield (t ha <sup>-1</sup> )	Grain N (%)	Stover Yield (t ha <sup>-1</sup> )	Stover N (%)
N Source	14.23***	10.45***	nd	nd
N Application Time	nd	nd	nd	nd
N Rate	NS	NS	nd	nd
Source * Time * Rate	nd	nd	nd	nd
Source * Time	nd	nd	nd	nd
Source * Rate	NS	NS	nd	nd
Time * Rate	nd	nd	nd	nd

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

nd - not done

NS - not significant

Tables 4.3 and 4.4 give the 1991 grain yield and grain N concentration data, respectively. There was a significant N source effect observed in 1991 with the LCM and FERT sources having 16 % and 14 % higher grain yields than the SBM source, respectively (Table 4.3). No other significant differences were observed (Table 4.2) and trends within other treatments or interactions were not obvious. It is worth noting that the check yield was greater than the N rate averaged SBM yield but was less than the N rate averaged LCM or FERT yield. The addition of large amounts of total C (Tables 1.1, 2.4) with the SBM N source may have led to significant immobilization of available N from the previous growing season. The corn on the SBM treated plots was observed to be somewhat chlorotic which can be a symptom of a N deficiency. The chlorosis was observed to be worse on the plots treated with high rates of SBM in the spring. Also of interest is the fact that the N rate averaged FERT and LCM plots only had a 10 % and 8 % larger grain yield than did the check plot, respectively. This suggests that there are high amounts of residual soil N in long term continuous corn cropping systems.

Table 4.3: N source and N rate effects on corn grain yield response at the Elora Research Station in 1991.

N Rate <sup>*</sup> (%)	N Source			Mean
	NH <sub>4</sub> NO <sub>3</sub>	Liquid Manure	Solid Manure	
	Yield (t ha <sup>-1</sup> )			
50	9.67	9.11	7.87	8.84
100	9.34	9.35	8.72	9.14
150	9.69	9.63	8.09	9.14
Mean	9.57 b <sup>***</sup>	9.36 b	8.23 a	9.04
Check <sup>**</sup>				8.67

\* N rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\* Check is the control plots that did not receive any N fertilizer.

\*\*\* N source means followed by different letters are significantly different at  $P \leq 0.05$ .

The grain N concentration indicated the same significant N source treatment effects as with grain yield (Table 4.2). The relative differences between rate averaged N sources and differences between check plots was also similar to the differences observed with grain yield (Tables 4.3 and 4.4).

Table 4.4: N source and N rate effects on grain N concentration response at the Elora Research Station in 1991.

N Rate <sup>*</sup> (%)	N Source			Mean
	NH <sub>4</sub> NO <sub>3</sub>	Liquid Manure	Solid Manure	
	-----N Concentration (%)-----			
50	1.51	1.34	1.31	1.39
100	1.52	1.43	1.24	1.39
150	1.55	1.39	1.33	1.42
Mean	1.53 a <sup>***</sup>	1.39 a	1.29 b	1.40
Check <sup>**</sup>				1.31

\* N rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\* Check is the control plots that did not receive any N fertilizer.

\*\*\* N source means followed by different letters are significantly different at  $P \leq 0.05$ .

## 4.3 1992 Results

### 4.3.1 Agronomic Events

Table 4.5 gives the significant management and crop development dates for the 1992 growing season. In addition to the normal agronomic practices, KCl was applied to several subplots which were sampled twice during the 1992 growing season. KCl was also applied to several different plots in December, 1992 and these were sampled in 1993. This data provided information with respect to the amount of chemical transport given a certain amount of net drainage and will be discussed in Chapter 5.

Table 4.5: Significant agronomic event dates for the 1992 growing season.

Date	Agronomic Event
May 13 - 15, 1992	Manures and fertilizer applied, plots ploughed
May 16, 1992	Pioneer 3902 corn planted @ 64000 plants ha <sup>-1</sup>
May 19, 1992	KCl applied to Fertilizer - Low - Spring plots
May 24, 1992	100 % Emergence
May 28, 1992	2-3 leaf stage
July 9, 1992	9-10 leaf stage
July 30, 1992	Onset of tasselling
October 14, 1992	Hand harvest for yield determination
Nov. 18-19, 1992	Manures and fertilizer applied, plots ploughed
December 8, 1992	KCl applied to Fertilizer-Low-Fall plots

#### 4.3.2 Stover and Grain Yields and N Concentrations

The cold and wet spring, summer and fall of 1992 produced below average yields and the crop was not harvested until October 15, 1992 (Table 4.5). In addition, the fall applied manures were not applied until late November due to poor weather conditions. Table 4.6 gives the summary of F values for the ANOVA of the various treatment effects for the 1992 yield and N concentration measurements. Tables 4.7, 4.8, 4.9 and 4.10 give the measured 1992 grain yield, grain N concentration, stover yield and stover N concentration, respectively.



Table 4.6: Summary of F values for the various treatments for the 1992 grain yield, grain N concentration, stover yield and stover N concentration.

Source of Variation	Grain Yield (t ha <sup>-1</sup> )	Grain N (%)	Stover Yield (t ha <sup>-1</sup> )	Stover N (%)
N Source	11.44 <sup>***</sup>	NS	NS	2.78 <sup>*</sup>
N Application Time	40.29 <sup>***</sup>	64.75 <sup>***</sup>	27.90 <sup>***</sup>	20.05 <sup>***</sup>
N Rate	10.37 <sup>***</sup>	12.58 <sup>***</sup>	7.05 <sup>***</sup>	11.39 <sup>***</sup>
Source * Time * Rate	NS	NS	NS	NS
Source * Time	NS	2.41 <sup>*</sup>	2.55 <sup>*</sup>	6.60 <sup>***</sup>
Source * Rate	2.28 <sup>*</sup>	NS	NS	NS
Time * Rate	NS	NS	NS	NS

<sup>\*</sup>, <sup>\*\*</sup>, <sup>\*\*\*</sup> Significant at a probability level of 0.10, 0.05 and 0.01, respectively.  
NS - not significant

Similar to 1991, there was a significant N source effect with respect to grain yield (Table 4.6). However, unlike in 1991, the SBM, LCM and FERT sources had decreased yields of 5.90, 5.53 and 5.08 t ha<sup>-1</sup> with all three being significantly different (Table 4.7). The observed trend in yields was the same for both application times which explains the lack of a significant time with source interaction. These data suggested that the plots fertilized with manure may not have been as susceptible to leaching in this wet growing season. While mineral N in the FERT plots may have been transported out of the root zone fairly rapidly, the manure plots may have been releasing their N gradually over the growing season. This was also indicated by the trend observed in the plots that received their N source in the fall of 1991 which may indicate that mineralization of previous applied manures may have been occurring.

When averaged over N source and N rate, the spring treatment yields were significantly greater than the fall treatment yields (Tables 4.6 and 4.7). Again, the leaching of the soil profile from the time of fall manure application to the next year's planting would have removed much of the plant available N and lower grain yields would be expected. When averaged over N source and application time, the high and medium rates (150 % and 100 %, respectively) were significantly

greater than the plots that received the low rates of N. There was no difference between the medium and high rates (Tables 4.6, 4.7). There was a slightly significant N source with N application rate effect (Table 4.6) but it was not shown in Table 4.7 for the sake of clarity. The effect was caused by the SBM plots which indicated that yields kept increasing with application rate (Table 4.7). This was not observed with the FERT and LCM sources. The overall average grain yield was 44 % greater than the control plot yields which suggested a decrease in residual N from the amount observed in 1991.

The grain N concentrations indicated slightly different statistical results from the grain yields. No significant N source effect was observed (Table 4.6). However, when averaged over N source and N rate, a significant application time effect was observed (Table 4.6). The spring plots had, on average, a 14 % greater grain N concentration content than the fall treated plots. In addition, when averaged over N source and application time, the plots that received the medium and high rates of application were 7 % and 10 % greater than the plots that received low application rates of N, respectively (Table 4.8). Again, the overall averaged grain N concentration content was 24 % greater than that for the control plot. The slightly significant N source with application time interaction (Table 4.6) was, again, due to the relatively high SBM grain N concentration at the high application rate.

Table 4.7: N source, N rate and application time effects on corn grain yield response at the Elora Research Station in 1992.

Grain Yield (t ha <sup>-1</sup> )				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
Spring	5.17	5.88	5.27	5.44
Fall	4.47	4.75	4.86	4.69
Mean	4.82	5.39	5.07	5.08 Aa *
Liquid Dairy Cattle Manure				
Spring	6.11	6.03	6.25	6.13
Fall	4.32	5.40	5.03	4.92
Mean	5.22	5.72	5.64	5.53 Ab
Solid Beef Manure				
Spring	5.25	6.80	6.77	6.27
Fall	4.87	5.47	6.23	5.52
Mean	5.06	6.13	6.50	5.90 Ac
N Source Means				
Spring	5.51	6.24	6.10	5.95 Ba
Fall	4.55	5.25	5.38	5.05 Bb
Mean	5.03 Ca	5.76 Cb	5.74 Cb	5.51
Check ***	3.82			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

Table 4.8: N source, N rate and application time effects on corn grain N concentration at the Elora Research Station in 1992.

Grain N Concentration (%)				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
	Spring	1.24	1.36	1.39
Fall	1.09	1.22	1.15	1.15
Mean	1.16	1.29	1.27	1.24
	Liquid Dairy Cattle Manure			
Spring	1.24	1.28	1.39	1.30
Fall	1.07	1.08	1.14	1.09
Mean	1.15	1.18	1.26	1.20
	Solid Beef Manure			
Spring	1.22	1.30	1.33	1.28
Fall	1.08	1.19	1.27	1.18
Mean	1.15	1.25	1.30	1.23
	N Source Means			
Spring	1.23	1.31	1.37	1.30 Aa *
Fall	1.08	1.16	1.19	1.14 Ab
Mean	1.16 Ba	1.24 Bb	1.28 Bb	1.22
Check ***	0.98			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

The same significant effects were observed with the stover yields as were observed with the grain N concentration values. Plots that received their N source in the spring of 1992 had, on

average, 20 % greater yields than those plots that received their N source in the fall of 1991. When averaged over N source and application time, there was no difference between the high and medium rates of manure application but they were 16 % and 14 % greater than those on the plots that received low rates of manure application, respectively (Table 4.9). Similarly, the overall average was 30 % greater than the control plot stover yield of  $2.06 \text{ t ha}^{-1}$ .

The stover N concentration content indicated a slightly significant N source effect with the FERT source being slightly greater than the two manures. Again, the N source and application rate averaged spring stover N concentration contents were 21 % greater than the stover N concentration contents in those plots that received N sources in the fall of 1991 (Table 4.10). Also there was no difference between the medium and high application rates although they were 20 % and 24 % greater than the low application rate plots, respectively (Table 4.10). Again, the slightly significant N source with application time (Table 4.6) was due to the SBM plots increasing with application rate whereas the FERT and LCM treatments indicated no difference between the high and medium rates of application (Table 4.10). On average the plots that received N had stover N concentration that were 71 % greater than that from the control plots (Table 4.10).

Table 4.9: N source, N rate and application time effects on corn stover yield response at the Elora Research Station in 1992.

Stover Yield (t ha <sup>-1</sup> )				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
Spring	2.65	2.97	2.77	2.79
Fall	2.21	2.55	2.60	2.45
Mean	2.43	2.76	2.69	2.62
	Liquid Dairy Cattle Manure			
Spring	2.86	3.08	2.97	2.97
Fall	1.97	2.29	2.32	2.19
Mean	2.41	2.69	2.65	2.58
	Solid Beef Manure			
Spring	2.51	3.22	3.13	2.95
Fall	2.34	2.48	3.03	2.62
Mean	2.42	2.85	3.08	2.79
	N Source Means			
Spring	2.67	3.09	2.96	2.91 Aa *
Fall	2.17	2.44	2.65	2.42 Ab
Mean	2.42 Ba	2.77 Bb	2.80 Bb	2.67
Check ***	2.06			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

Table 4.10: N source, N rate and application time effects on corn stover N concentrations at the Elora Research Station in 1992.

Stover N Concentration (%)				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
Spring	0.55	0.72	0.69	0.65
Fall	0.45	0.51	0.44	0.46
Mean	0.50	0.61	0.56	0.56
	Liquid Dairy Cattle Manure			
Spring	0.58	0.54	0.60	0.57
Fall	0.40	0.54	0.54	0.49
Mean	0.49	0.54	0.57	0.53
	Solid Beef Manure			
Spring	0.39	0.53	0.59	0.50
Fall	0.40	0.50	0.59	0.50
Mean	0.39	0.51	0.59	0.50
	N Source Means			
Spring	0.51	0.59	0.63	0.58 Aa *
Fall	0.42	0.51	0.52	0.48 Ab
Mean	0.46 Ba	0.55 Bb	0.57 Bb	0.53
Check ***	0.31			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

## 4.4 1993 Results

### 4.4.1 Agronomic Events

Table 4.11 gives the significant management and crop development dates for the 1993 growing season. The 1993 growing season was characterized by fairly normal air temperatures, below normal spring precipitation, above average summer precipitation and approximately normal fall precipitation. Shortly after planting, cool temperatures delayed emergence for approximately 3 weeks. However, average to above average temperatures and timely precipitation resulted in good growth and the crop was tasselling by early August (Table 4.11). Differences in corn stover growth between treated plots were obvious but not differences in grain.

Table 4.11: Significant agronomic event dates for the 1993 growing season.

Date	Agronomic Event
May 10, 1993	Liquid dairy cattle manure applied and ploughed
May 11, 1993	Solid beef manure applied and ploughed
May 12, 1993	Fertilizer applied ; plots cultivated
May 13, 1993	Pioneer 3902 corn planted @ 64000 plants ha <sup>-1</sup>
May 21, 1993	"Dual" and "Bladex" sprayed
June 2, 1993	Chloride pulse applied for detailed transport experiment
June 7, 1993	100 % emergence
June 12, 1993	2-3 leaf stage
July 24, 1993	9-10 leaf stage
August 2, 1993	Onset of tasselling
August 15, 1993	Silking complete
November 3, 1993	Hand harvest of plots

### 4.4.2 Stover and Grain Yields and N Concentrations

Table 4.12 gives the summary of F values from the ANOVA of the 1993 grain yield, grain N concentrations, stover yield and stover N concentrations and Tables 4.13 through 4.16 give the



respective measured values. Note that significant differences for interaction effects are not given for the sake of clarity.

Table 4.12: Summary of F values for the various treatments for the 1993 grain yield, grain N concentrations, stover yield and stover N concentrations.

Source of Variation	Grain Yield (t ha <sup>-1</sup> )	Grain N (%)	Stover Yield (t/ha)	Stover N (%)
N Source	NS	NS	4.37 <sup>**</sup>	NS
N Application Time	21.17 <sup>***</sup>	28.56 <sup>***</sup>	14.27 <sup>***</sup>	3.05 <sup>*</sup>
N Rate	14.54 <sup>***</sup>	28.66 <sup>***</sup>	8.16 <sup>***</sup>	4.03 <sup>*</sup>
Source * Time * Rate	NS	NS	NS	NS
Source * Time	NS	NS	NS	NS
Source * Rate	3.64 <sup>**</sup>	NS	NS	NS
Time * Rate	3.1 <sup>*</sup>	NS	NS	NS

<sup>\*</sup>, <sup>\*\*</sup>, <sup>\*\*\*</sup> Significant at a probability level of 0.10, 0.05 and 0.01, respectively.  
NS - not significant

All treated plots had grain yields that were larger than the yield measured in the control plots. Unlike in 1992, there was no significant N source effect in 1993 (Table 4.12). Yields were slightly larger and lower in 1993 than in 1992 and 1991, respectively. The lack of yield differences between the N sources was attributed to the normal amounts of summer precipitation received in 1993 which resulted in little downwards movement of N during the growing season. This was consistent with the Cl<sup>-</sup> transport experiments presented in Chapter 5.

When averaged over N application times and N sources, the low N rate was significantly lower than the medium or high N rate grain yields. This was most obvious in the SBM treated plots where it is assumed that much of the available N at the lower application rate was immobilized. This has important implications regarding the amount of N reaching the groundwater. Similar to the 1992 grain yields, the N source and N application rate averaged spring treated plots were 11 % larger than the fall treated plots (Table 4.13).

Grain N concentrations indicated significant N application time and N application rate effects (Table 4.12). The lack of a significant source effect was consistent with the grain yield values (Table 4.14) and was attributed to normal precipitation amounts received in the 1993 growing season (Figure 2.3). The 1993 grain N concentration for the check plots remained approximately equal to the 1992 value. The 1993 overall average grain N concentration was only 7 % lower and 7 % greater than the 1991 and 1992 values, respectively. This trend was fairly consistent within all treatments. On average, the spring treated plots had grain N concentrations that were 10 % greater than the fall treated plots. Unlike the 1992 results, there were significant differences between all three application rates with the high rates being 4 % and 17 % greater than the medium and low rates, respectively. These N application rate differences were consistent within each N source and N application time.

Stover yields indicated significant differences between N sources, N application rates and N application times (Table 4.12). All of the treated plots had corn stover yields that were greater than the control plots. There was no difference between the N rate and N application time averaged FERT and LCM sources but, on average, these two sources were 13 % greater than the SBM corn stover yield (Table 4.15). Again, this difference appears to be due to the reduced yields of the SBM low N rate treated plots.

On average, the spring treated plots were 16 % greater than the fall treated plots (Table 4.15). Again, this was attributed to a loss of fall applied N through the November to April leaching periods. On average, there was no difference between the high and medium N application rates but, they were 19 % greater than the low N application rate plots. The reduced grain and stover yields in the SBM low N application rate treated plots was consistent with reduced N measured in the soil solution.

The 1993 stover N concentration values indicated similar differences and trends as the 1993 grain N concentration values. Overall, the treated plots had stover N concentrations that were 36 % higher than the control plot stover N concentrations. There was no significant source effect but there were significant N application time and N application rate effects (Tables 4.12 and 4.16). On

average the spring treated plots were 9 % greater than the fall treated plots (Table 4.16). On average the high application rate plots were 8 % and 14 % greater than the medium and low application rate plots, respectively. The N application time effect was most obvious in the plots which received  $\text{NH}_4\text{NO}_3$  as their N source. There was no N application time differences in the plots which received LCM and SBM as their N source. This was attributed to the two manure N sources mineralizing their N slowly over the winter leaching period so that there are less leaching losses.

Table 4.13: N source, N rate and N application time effects on corn grain yield response at the Elora Research Station in 1993.

Grain Yield (t ha <sup>-1</sup> )				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
Spring	6.29	6.95	6.57	6.60
Fall	5.29	6.26	5.99	5.85
Mean	5.79	6.60	6.28	6.23
	Liquid Dairy Cattle Manure			
Spring	6.41	6.04	6.78	6.41
Fall	5.47	6.38	5.90	5.92
Mean	5.94	6.21	6.34	6.16
	Solid Beef Manure			
Spring	5.98	6.77	6.93	6.56
Fall	4.33	5.97	7.01	5.77
Mean	5.15	6.37	6.97	6.16
	N Source Means			
Spring	6.22	6.58	6.76	6.52 Aa
Fall	5.03	6.20	6.30	5.85 Ab
Mean	5.63 Ba	6.39 Bb	6.53 Bb	6.19
Check ***	3.65			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

Table 4.14: N source, N rate and application time effects on corn grain N concentration at the Elora Research Station in 1993.

Grain N Concentration (%)				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
	1.31	1.43	1.49	1.41
Spring				
Fall	1.15	1.33	1.32	1.27
Mean	1.23	1.38	1.40	1.34
Liquid Dairy Cattle Manure				
Spring	1.34	1.38	1.41	1.38
Fall	1.10	1.23	1.38	1.23
Mean	1.22	1.31	1.39	1.31
Solid Beef Manure				
Spring	1.21	1.34	1.44	1.33
Fall	1.09	1.31	1.38	1.26
Mean	1.15	1.33	1.41	1.30
N Source Means				
Spring	1.29	1.38	1.45	1.37 Aa
Fall	1.11	1.29	1.36	1.25 Ab
Mean	1.20 Ba	1.34 Bb	1.40 Bc	1.31
Check ***	0.95			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

Table 4.15: N source, N rate and application time effects on corn stover yield response at the Elora Research Station in 1993.

Stover Yield (t ha <sup>-1</sup> )				
Application Time	Application Rate **			
	50	100	150	Mean
Spring	NH <sub>4</sub> NO <sub>3</sub>			
	4.76	5.67	5.31	5.25
	4.17	4.61	4.71	4.50
	4.47	5.14	5.01	4.87 Aa
Liquid Dairy Cattle Manure				
Spring	4.87	4.90	5.29	5.02
Fall	4.10	4.72	4.41	4.41
Mean	4.48	4.81	4.85	4.71 Aa
Solid Beef Manure				
Spring	4.01	5.22	4.52	4.59
Fall	2.67	4.21	4.84	3.91
Mean	3.34	4.72	4.68	4.24 Ab
N Source Means				
Spring	4.55	5.26	5.04	4.95 Ba
Fall	3.65	4.51	4.65	4.27 Bb
Mean	4.10 Ca	4.89 Cb	4.85 Cb	4.61
Check ***	2.90			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

Table 4.16: N source, N rate and application time effects on stover N concentration at the Elora Research Station in 1993.

Stover N Concentration (%)				
Application Time	Application Rate **			
	50	100	150	Mean
	NH <sub>4</sub> NO <sub>3</sub>			
Spring	0.58	0.74	0.74	0.69
Fall	0.54	0.61	0.62	0.59
Mean	0.56	0.67	0.68	0.64
Liquid Dairy Cattle Manure				
Spring	0.62	0.53	0.63	0.59
Fall	0.51	0.59	0.65	0.58
Mean	0.56	0.56	0.64	0.59
Solid Beef Manure				
Spring	0.61	0.54	0.65	0.60
Fall	0.56	0.59	0.60	0.58
Mean	0.58	0.57	0.62	0.59
N Source Means				
Spring	0.60	0.60	0.67	0.63 Aa
Fall	0.53	0.59	0.62	0.58 Ab
Mean	0.57 Aa	0.60 Ab	0.65 Ac	0.61
Check ***	0.45			

\* The first letter denotes which values are being compared and different second letters indicate significant differences at the 0.05 probability level within those values being compared.

\*\* Application rate is expressed as a percentage of the recommended rate for the N source in question. See Table 2.4 for recommended application rates.

\*\*\* Check is the control plots that did not receive any N fertilizer.

#### 4.4.3 Leaf Area Index and Crop Height

Leaf area index (LAI) and crop height were measured throughout the 1993 growing season as explained in section 2.4.6.3 and are given in Appendix 6. This data was required to estimate evapotranspiration amounts using the Elora Research Station evapotranspiration model (Appendix 2). Equations to simulate LAI and crop height are presented in the model description (Appendix 2). Figures 4.1 and 4.2 give the LAI and crop height versus the number of days after emergence, respectively. Both figures indicate the sigmoidal shape that is often used to describe the growth of certain annual plants.

Figure 4.1: Measured leaf area index versus the number of days after emergence, 1993.

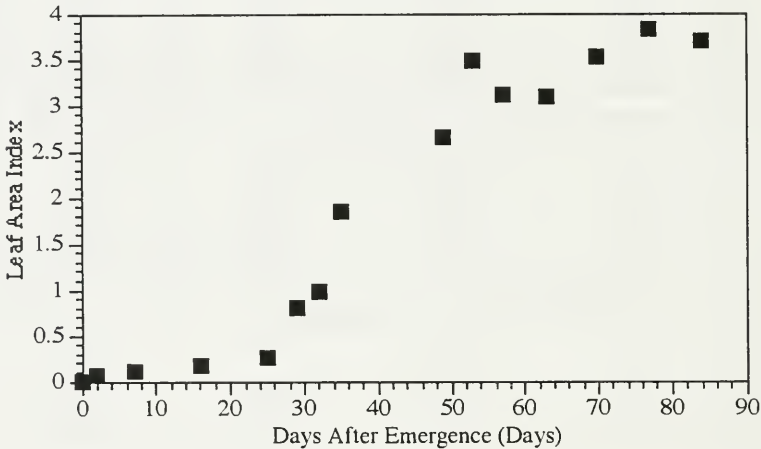
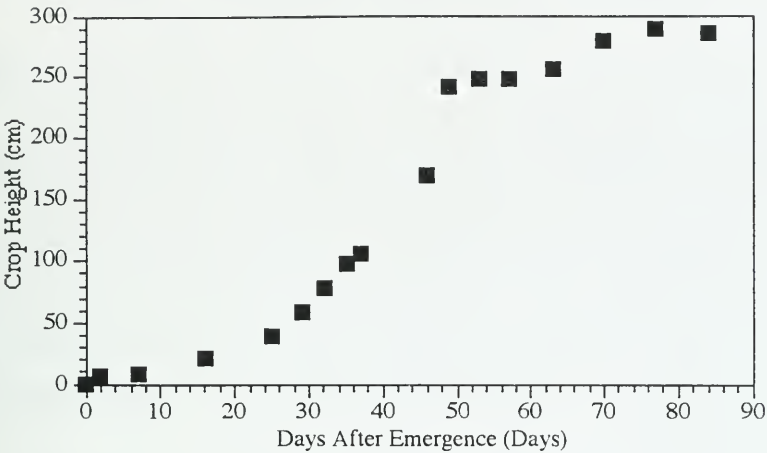




Figure 4.2: Measured crop height versus the number of days after emergence, 1993.



#### 4.5 Summary

The 1991 growing season had relatively normal temperatures and precipitation amounts during the growing season. This resulted in above average yields for this year. The grain yield and grain N concentration were only interpreted in terms of N source and application rate for this year as it was the first year of the experiment. Similar differences and trends between treatments were observed for both variables and a significant source effect was observed. When averaged over application rates, there was no difference between the grain yields with the FERT and LCM sources but they were 16 % and 14 % greater than the grain yield with the SBM source, respectively (Table 4.3). This may be an indication of large amounts of immobilization of N in the SBM plots due to large additions of C. The overall grain yield average was only 4 % greater than that from the control plots which was indicative of high residual N contents following a continuous corn cropping system.

The 1992 growing season was characterized by below average temperatures and well above normal amounts of precipitation. This resulted in below normal grain yields and lower grain N concentrations relative to 1991. Significant N source effects were only observed in the grain yields

in the order of SBM > LCM > FERT. Significant application rates were observed with grain and stover yields and grain and stover N concentrations in the order of high = medium > low. Significant N source with N application time interactions were observed in stover yield, grain N and stover N concentrations. The significance was attributed to the SBM source which consistently indicated increases in these variables with application rates. Relative to 1991, the lower yields and N contents may have resulted from increased leaching throughout the growing season due to the large amounts of precipitation. The data suggested that the manures, especially SBM, were able to mineralize N over the growing season so that it was less susceptible to leaching and more amenable for plant uptake. In contrast, the FERT source would be susceptible to nitrification and leaching as soon as it was applied to the plots. Consequently, less N would be available for plant uptake and lower yields would be expected.

The 1993 growing season was characterized by normal air temperatures, below normal spring precipitation, slightly above normal summer precipitation and normal fall precipitation. Grain and stover yields were slightly greater than the corresponding 1992 yields. No significant N source effects were observed with grain yields. This was attributed to a lack of movement of N through the root zone. On average, spring treated plots were 11 % greater than fall treated plots. The high N application rate treated plots were the same as the medium treated plots but, on average, they were 15 % greater than the low treated plots. Significant N source, N application rate and N application time effects were observed with corn stover yields.

Grain N concentrations indicated significant N application time and N application rate effects. The lack of a significant N source effect was consistent with the grain yield results. Stover N concentrations indicated similar differences as grain N concentrations. N application time effects were most obvious in the FERT N source treated plots. The plots that were treated with the two manure sources had negligible N application time effects which was attributed to mineralization of N over the winter leaching period.

## Chapter 5 Chemical Transport

### 5.1 Introduction

This chapter presents the results from the  $\text{Cl}^-$  tracer experiments that were carried out in 1992 and 1993. The methodology that was used to collect and analyse the soil samples for  $\text{Cl}^-$  was presented in section 2.4.7 and the data for all experiments are given in Appendix 7. In addition, summaries of the soil solution concentrations of  $\text{NO}_3^- - \text{N}$  and  $\text{NH}_4^+ - \text{N}$  throughout the length of the project will be presented. The methodology that was used to collect and analyse the soil solution samples was discussed in section 2.4.2. Due to the size of the soil solution data files as well as some other files, they have been placed on a diskette which is found at the back of this report. Appendix 8 gives a list of the file names and their contents' that are found on the diskette.

### 5.2 $\text{Cl}^-$ Tracer Experiments

#### 5.2.1 1992 Subplot Tracer Experiments

As discussed in section 2.4.7,  $100 \text{ g m}^{-2}$  of  $\text{Cl}^-$  was applied to four subplots in the spring of 1992. These plots were sampled twice during the growing season to a depth of 1 m in 0.10 m increments. Since the plots were only sampled twice, this data will be used to demonstrate the type of interpretations that can be made from this type of experiment. The 1993 data is more complete and will be presented in section 5.2.2. Figure 5.1 gives the mass of  $\text{Cl}^-$  as a function of depth for both sampling dates. It should be noted that the sampling dates also represent a specific amount of net drainage since the date of  $\text{Cl}^-$  application on May 19, 1992 (Appendix 4).

Figure 5.1: Mass of  $\text{Cl}^-$  as a function of depth for June 4, 1992 and August 10, 1992.

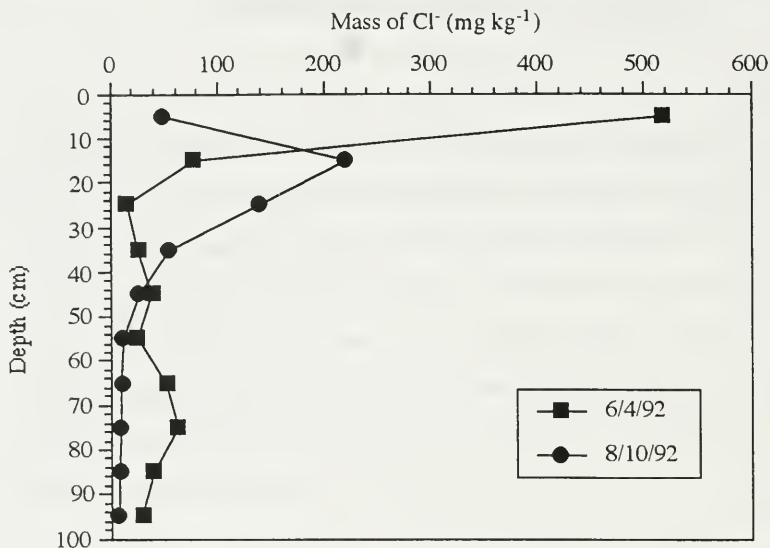


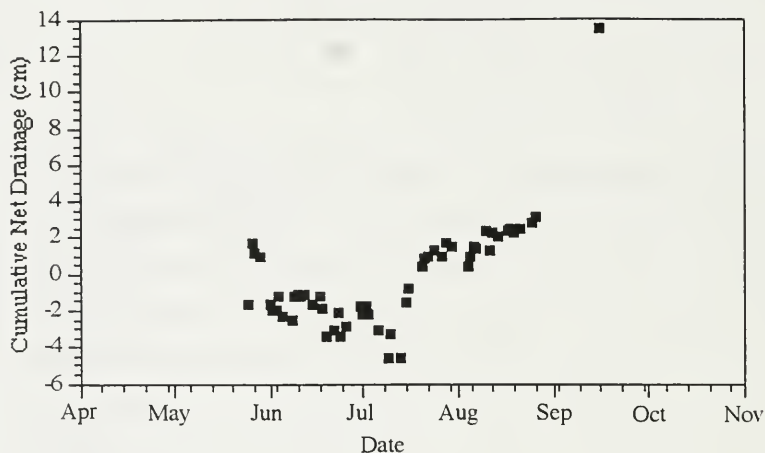
Figure 5.2 gives the cumulative amount of net drainage versus time over the 1992 growing season. Approximately -1.39 cm of net drainage occurred from the time of  $\text{Cl}^-$  application to the first sampling date of June 4, 1992 (Appendix 4, Figure 5.2). This explains the lack of movement of the  $\text{Cl}^-$  downwards through the soil profile (Figure 5.1). There is no physical explanation for the increase in the amount of  $\text{Cl}^-$  from the 30 cm to the 1 m depth except that it was most likely caused by contamination of the lower samples during sampling. For this reason, analysis of these data only uses the  $\text{Cl}^-$  in the top 30 cm. Similarly, the analysis of the August 10, 1992 sampling date only uses the  $\text{Cl}^-$  in the top 70 cm.

Approximately 2.3 cm of net drainage had occurred by the August 10, 1992 sampling date (Appendix 4, Figure 5.2). If the  $\text{Cl}^-$  had been using all of the wetted pore space to move through the soil profile, then the distance that the center of mass of the  $\text{Cl}^-$  would have moved through can be calculated by the following formula:

$$d = \frac{I}{\theta_v} \quad [5.1]$$

The average soil water content between May 19, 1992 and August 10, 1992 was  $0.33 \text{ cm}^3 \text{ cm}^{-3}$  (Appendix 1). Eq. [5.1] predicts that the center of mass of the  $\text{Cl}^-$  would have moved approximately 7 cm into the soil profile by August 10, 1992. Figure 5.1 indicated that the centre of mass had moved to approximately the 20 cm depth. Although Eq. [5.1] is valid for steady state conditions ( $\partial\theta_v / \partial t = 0$ ), this analysis might suggest that the  $\text{Cl}^-$  is not using all of the wetted pore space to move through the soil profile. This is often the case in field soils where the water moves through macropores and / or biopores and bypasses much of the soil matrix. However, Figure 5.2 indicates that net drainage became positive in mid July. If the  $\text{Cl}^-$  did not move until this time, a water balance could be used from July 7 to August 10, 1992 to calculate the amount of net drainage that would have moved the  $\text{Cl}^-$ . Using Appendices 1 and 4, a net drainage of approximately 8 cm left the 0 - 40 cm depth. With an average soil water content of approximately  $0.37 \text{ cm}^3 \text{ cm}^{-3}$  during this time, Eq. [5.1] would predict that the  $\text{Cl}^-$  would have moved to about the 20 cm depth which was observed in Figure 5.1. This analysis together with the fact that Figure 5.1 is a unimodal breakthrough curve suggests that during periods of positive net drainage, the  $\text{Cl}^-$  moves through a single pore domain in this soil.

Figure 5.2: Cumulative net drainage past the 80 cm depth over the 1992 growing season.



The area under each of the curves in Figure 5.1 multiplied by the bulk density of each layer (Table 3.1) gives the amount of  $\text{Cl}^-$  per unit area that was recovered in the profile. The area under the curves was calculated by integration using Mathcad software (MathSoft Inc., 1992) and the program is given in Appendix 9. This can be compared with the surface applied amount of  $\text{Cl}^-$  to examine how much  $\text{Cl}^-$  has moved through the soil profile. Table 5.1 gives the amounts of  $\text{Cl}^-$  recovered for each sampling date and the amount of  $\text{Cl}^-$  that was assimilated by the corn as measured at the end of the growing season. Plant uptake of  $\text{Cl}^-$  at the June 4, 1992 sampling date can be considered negligible since this was approximately only 10 days after emergence (Table 4.5). These mass recoveries are for those depths mentioned above and the values are representative of similar solute transport experiments (Younie, 1993; Van Wesenbeeck and Kachanoski, 1991).

Table 5.1: Mass of  $\text{Cl}^-$  recovered in the soil profile and in the corn plants (1992).

Date	$\text{Cl}^-$ recovered in soil profile / corn plants ( $\text{g m}^{-2}$ )
June 4, 1992	84.4
August 10, 1992	71.6
Plant Uptake	3.30

### 5.2.2 1993 Subplot Tracer Experiments

As discussed in section 2.4.7,  $100 \text{ g m}^{-2}$  of  $\text{Cl}^-$  was applied, on December 8, 1992, to four subplots of those plots that received low rates of fertilizer in the fall of 1992. Figure 5.3 gives the amount of  $\text{Cl}^-$  in the soil profile at the various sampling times throughout the 1993 growing season. Figures 5.4 and 5.5 give the cumulative net drainage past the 40 cm and 80 cm depths for the 1993 growing season, respectively.

Figure 5.3: Mass of  $\text{Cl}^-$  as a function of depth for various dates throughout the 1993 growing season.

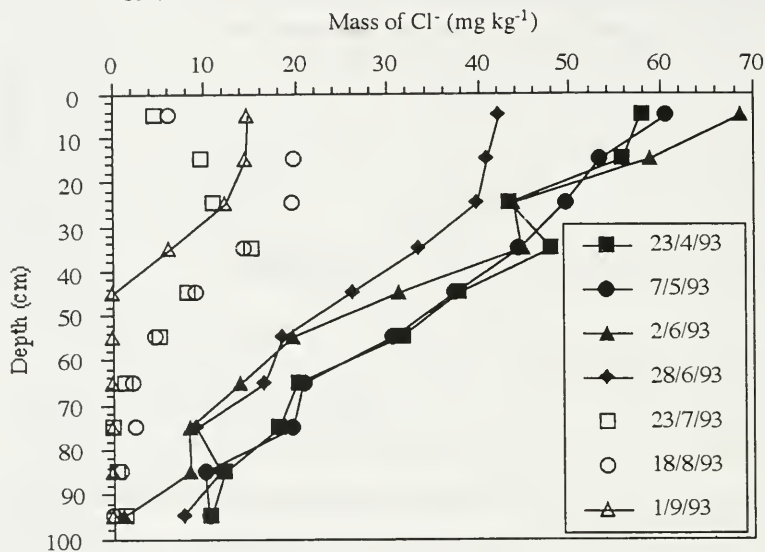


Figure 5.4: Cumulative net drainage past the 40 cm depth over the 1993 growing season.

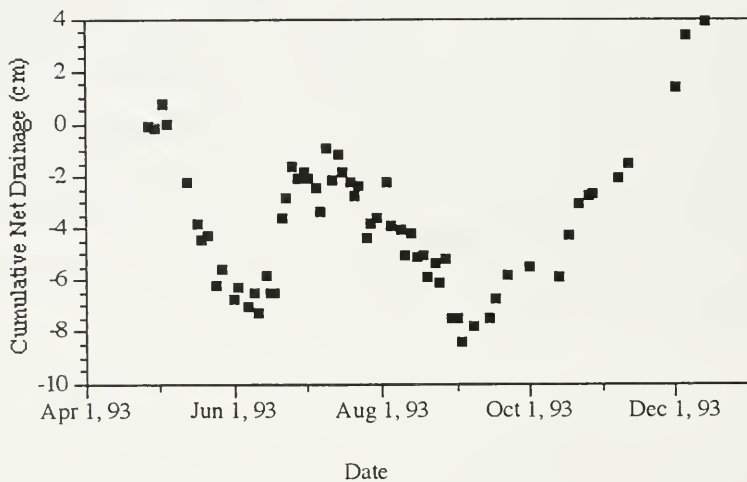
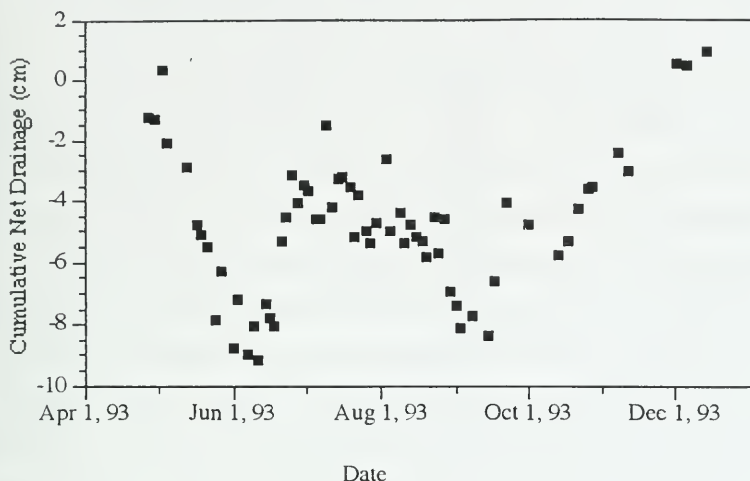




Figure 5.5: Cumulative net drainage past the 80 cm depth over the 1993 growing season.



A comparison of Figures 5.2 and 5.5, in conjunction with Figure 2.3, provides information with regards to how the  $\text{Cl}^-$  was being leached in each year. Figures 5.2 and 5.5 indicated that the cumulative net drainage decreased early in the growing season in each of the two years. The decrease was more dramatic in 1993 due to below normal amounts of spring precipitation (Figure 2.3). This is the normal situation at this site as evapotranspiration becomes greater than precipitation during the summer months. However, in 1992, large amounts of precipitation from July through November (Figure 2.3) meant that the situation was reversed and net drainage occurred from mid July through the fall (Figure 5.2). The positive net drainage meant that the soil profile was being leached continually throughout the latter half of 1992. The situation in 1993 was more typical of what happens at this site during the growing season. The net drainage decreased during the spring and remained negative until the soil profile was recharged and began to drain in mid November. These two scenarios also help to explain the differences observed in the leaching patterns observed with the  $\text{Cl}^-$  data (Figures 5.1, 5.3). In 1992, the  $\text{Cl}^-$  moved as a 'pulse' once the net drainage became positive in mid July. In 1993, net drainage was negative and did not occur

throughout the growing season. Therefore, the  $\text{Cl}^-$  would have been moved downwards with percolating rainfall and back up by the AET demand. As a result of this continual up and down movement, the  $\text{Cl}^-$  was continually being diffused throughout the profile. The result is a lack of a definable peak in  $\text{Cl}^-$  concentration as the  $\text{Cl}^-$  'leaks' from the soil profile rather than if it had moved through as a 'pulse'. However, the large amount of June and July, 1993 precipitation amounts meant that the  $\text{Cl}^-$  near the soil surface began to move as a pulse (Figure 5.3). The lower August and September precipitation amounts meant that AET was greater than precipitation and the  $\text{Cl}^-$  moved towards the surface (August 18 and September 1 sampling dates in Figure 5.3). Once again, the distribution of  $\text{Cl}^-$  on the September 1 sampling date indicated more of a 'leaky'  $\text{Cl}^-$  movement than a pulse type movement (Figure 5.3). With respect to  $\text{NO}_3^-$  - N leaching, a soil profile under the 1993 conditions would not have any losses of  $\text{NO}_3^-$  - N leaching out of the root zone during the growing season. It should be noted, however, that the movement of  $\text{Cl}^-$  in 1992 is probably typical of leaching at this site in the fall and early spring periods (ie. positive net drainage). Therefore, it is especially important to limit the amount of chemical that is in the soil profile during these times of maximum leaching.

Table 5.2 gives the mass of  $\text{Cl}^-$  per unit area recovered, in the soil profile, for the various dates in 1993. Note that the  $\text{Cl}^-$  was applied on December 8, 1992 and that 47.4 % ( $1 - (52.6/100)$ ) had been leached prior to sampling on April 23, 1993. Again, this indicated the importance of the fall and spring leaching periods and minimizing the amount of chemical left in the soil profile during these periods. Table 5.2 supports the idea that the  $\text{Cl}^-$  was 'leaking' from the soil profile over the growing season. The sharp loss of mass from the end of June to the July sampling date is consistent with the net drainage calculations which indicated that water was perhaps draining from the soil profile at this time.

Table 5.2: Mass of  $\text{Cl}^-$  recovered in the soil profile and in the corn plants (1993).

Date	$\text{Cl}^-$ recovered in soil profile / corn plants ( $\text{g m}^{-2}$ )
April 23, 1993	52.6
May 7, 1993	52.8
June 2, 1993	45.1
June 28, 1993	38.3
July 23, 1993	8.8
August 18, 1993	11.8
September 1, 1993	6.6
Plant Uptake	3.1

It is of interest to calculate the percentage of  $\text{Cl}^-$  lost from a specific depth interval as a function of cumulative net drainage. For example, the relative mass of  $\text{Cl}^-$  lost from the 0 - 80 cm or the 0 - 40 cm depths, after a specific amount of cumulative net drainage can be calculated as the difference from what was applied and what was remaining. These calculations will be discussed in the next section.

### 5.2.3 Detailed $\text{Cl}^-$ Experiment

As was discussed in section 2.4.7, a detailed  $\text{Cl}^-$  transport experiment was also performed throughout the 1993 growing season. Soil samples from this experiment were taken in 0.05 m increments to a depth of 0.80 m. The sampling depth increment was decreased in order to make more detailed measurements regarding the movement of  $\text{Cl}^-$  given a specific amount of net drainage. Figure 5.6 gives the mass of  $\text{Cl}^-$  as a function of depth for the various sampling dates. Figure 5.7 gives the relative mass of  $\text{Cl}^-$  that was remaining in the 0 - 40 cm depth versus the cumulative net drainage and Table 5.3 gives the relative mass remaining in the 0 - 40 cm and 0 - 80 cm depths as well as the amount of plant assimilated  $\text{Cl}^-$ . Net drainage was calculated from the day the  $\text{Cl}^-$  was applied (June 2, 1993). The mass remaining in the 0 - 40 cm depth was chosen to illustrate the

mass loss process as little  $\text{Cl}^-$  had moved past the 80 cm depth by the end of 1993. The MathCAD (Mathsoft Inc, 1992) program used to calculate the mass remaining to a specific depth is given in Appendix 9. Figure 5.6 was used to determine that the  $\text{Cl}^-$  began moving out of the 0 - 40 cm depth after the July 15 sampling date. The fraction of the initial amount of  $\text{Cl}^-$  remaining in the 0 - 40 cm depth is simply the ratio of the amount in the 0 - 40 cm depth to the amount in the 0 - 80 cm depth on each sampling date.

Table 5.3: Mass of  $\text{Cl}^-$  recovered in the soil profile and in the corn plants for the 1993 detailed  $\text{Cl}^-$  experiment.

Date	$\text{Cl}^-$ recovered in soil profile / corn plants ( $\text{g m}^{-2}$ )	
	0 - 40 cm	0 - 80 cm
June 23, 1993	70.43	72.14
July 15, 1993	61.98	65.24
August 9, 1993	85.38	95.27
September 1, 1993	85.23	90.42
October 26, 1993	81.76	116.91
November 25, 1993	30.56	62.94
December 14, 1993	23.63	54.05
Plant Uptake	3.45	3.45

Figure 5.6: Mass of  $\text{Cl}^-$  as a function of depth for various dates throughout the 1993 growing season from the detailed  $\text{Cl}^-$  experiment.

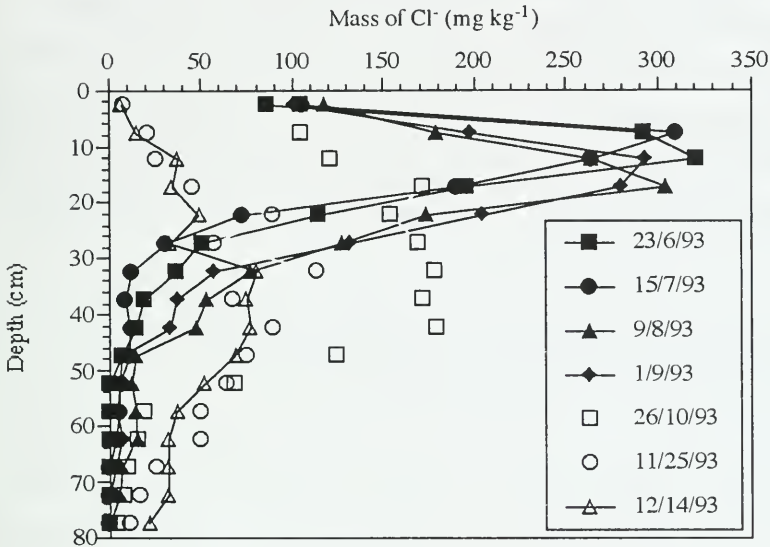


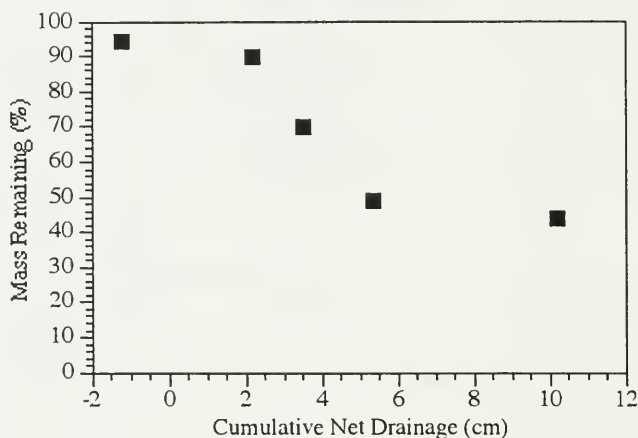
Figure 5.6 indicated how quickly  $\text{Cl}^-$  could be lost from the soil profile once net drainage becomes positive. The first four sampling dates show the  $\text{Cl}^-$  to be relatively immobile with just some up and down movement most likely in response to large rainfall events. It is interesting to note that the  $\text{Cl}^-$  becomes more disperse with each up and down movement. In addition, once the downwards movement dominates, the  $\text{Cl}^-$  becomes much more disperse, the peak concentrations decrease and the  $\text{Cl}^-$  is removed from the soil profile quite rapidly (Figure 5.6, Table 5.3).

Figure 5.7 gives the relative mass remaining in the 0 - 40 cm depth versus cumulative net drainage. This type of relationship can be described by the exponential equation:

$$M_r = e^{-kI} \quad [5.2]$$

where  $M_r$  is the relative mass remaining,  $I$  ( $L_w^3 L_b^{-2} T^{-1}$ ) is the cumulative net drainage and  $k$  ( $T L_b^2 L_w^{-3}$ ) is the rate constant. Here, parameter units are given as dimensions where  $M$  is mass,  $T$  is time,  $L_b$  is bulk length and  $L_w$  is fluid length. The relative mass remaining data can be used in conjunction with the soil N measurements to estimate the flux concentration of  $NO_3^- - N$  that was being leached through the soil profile. Multiplying Eq. [5.2] by the amount of  $NO_3^- - N$  ( $M L_b^{-2}$ ), at the lower depth of the soil profile, and dividing by  $I$  will give the flux concentration of  $NO_3^- - N$  ( $M L_w^{-3}$ ). This data can then be compared with the measured solution sampler concentrations of  $NO_3^- - N$ .

Figure 5.7: Relative mass of  $Cl^-$  remaining in the 0 - 40 cm depth in the detailed experiment.



Note that the negative cumulative net drainage point (-1.21 cm) represents the September 1, 1993 sampling date. The August 9, 1993 sampling date indicated less  $Cl^-$  remaining in the 0 - 40 cm depth than the September 1 date. This is consistent with the calculated cumulative net drainage values which indicated that increased AET throughout August would have caused some of the  $Cl^-$  to move back up into the 0 - 40 cm depth. Thus, even though the soil was sampled at a later time, there was an increase in the amount of  $Cl^-$  in the 0 - 40 cm depth.

Figure 5.7 indicated that approximately 60 % of the  $\text{Cl}^-$  has left the 0 - 40 cm depth after 10 cm of cumulative net drainage since application of the  $\text{Cl}^-$ . Table 5.3 indicated that after 10.5 cm of net drainage, approximately 46 % ( $1 - 54.05 / 100$ ) of the  $\text{Cl}^-$  had left the 0 - 80 cm depth. It should be noted that these amounts of net drainage are underestimated since the net drainage calculations included the amount of water it took to recharge the soil profile. The amounts of net drainage would be larger if the period of actual  $\text{Cl}^-$  movement was only considered since the  $\Delta$  storage term would have been negligible. It is also of interest to note that over the period of maximum leaching when the  $\Delta$  storage can be considered negligible (November - April) there is approximately 39 cm of precipitation (Table 2.2). If the average water content is  $0.40 \text{ cm}^3 \text{ cm}^{-3}$ , the percolating water could move down to the 1 m depth. This value is slightly overestimated as runoff and winter sublimation are disregarded. This value is consistent with the fact that approximately half of the  $\text{Cl}^-$  has been removed from the 0 - 80 cm depth in the 1993 fall leaching period. This was also consistent with the amount of  $\text{Cl}^-$  remaining in the spring of 1993 after being applied on December 8, 1992 (Table 5.2). In fact, the analysis of soil samples that were taken on March 30, 1994 indicated that there was generally less than  $5 \text{ mg Cl kg}^{-1}$  at any depth in the soil profile down to 1.2 m. It is reasonable to expect that little of the 1993 applied  $\text{Cl}^-$  will remain by the end of the 1994 spring leaching period. Again, this emphasizes the importance of limiting the amount of N available for leaching that is in the soil profile at the end of each crop year.

#### 5.2.4 Summary of $\text{Cl}^-$ Leaching Experiments

A water deficit during prevents chemicals from leaching downwards through the soil profile at this site during normal growing season conditions such as in 1991 and 1993. The small upwards and downwards movement of  $\text{Cl}^-$  during the growing season, in response to rainfall events, serves to disperse the  $\text{Cl}^-$  and produce smaller peak concentrations. However, 1992 was a very wet growing season and  $\text{Cl}^-$  was observed to leach through the soil profile with infiltrating rainfall. Consequently,  $\text{NO}_3^-$  was also being leached out of the root zone which resulted in reduced grain and stover yields on those plots which received  $\text{NH}_4\text{NO}_3$  and LCM. Only 50 % of the  $\text{Cl}^-$  applied



in December, 1992 was found to be remaining in the soil profile in April of 1993. Also, 50 % of the  $\text{Cl}^-$ , applied in June, 1993, was shown to leach past the 80 cm depth from October through December. This suggests that any chemical (ie.  $\text{NO}_3^-$ ) capable of moving with infiltrating water, has the possibility of being leached through the soil profile during the October through April leaching period. This indicated the importance of minimizing the amounts of these chemicals in the soil after the time of harvest.

### 5.3 Soil Solution Samples of $\text{NO}_3^-$ - N and $\text{NH}_4^+$ - N

As discussed in section 2.4.2, two solution samplers were installed at the 0.80 m depth in all plots. These were used to sample the soil solution concentrations of  $\text{NO}_3^-$  - N and  $\text{NH}_4^+$  - N throughout the growing season. The samplers yielded minimal samples in 1991 and had approximately a 65 % and 90 % success rate in 1992 and 1993, respectively. ANOVAs were performed on the 1992 and 1993 data for each sampling date. ANOVAs between years were not performed since different climatic conditions make the assumption of sample independence invalid. The measured concentrations are on the computer diskette at the back of this report and the file names are explained in Appendix 8. The various treatments for each plot were defined in section 2.3.

#### 5.3.1 1991 Results

Figures 5.8 through 5.13 give the  $\text{NO}_3^-$  - N concentrations measured throughout the 1991 growing season. Note that  $\text{NH}_4^+$  - N concentrations are not discussed as the concentrations were generally less than  $5 \text{ mg L}^{-1}$  and were usually less than  $2 \text{ mg L}^{-1}$ . A concentration of  $2 \text{ mg L}^{-1}$  and a net drainage of 20 cm would mean a loss of only  $4 \text{ kg N ha}^{-1}$ . The data are presented for general comparisons only since all plots did not yield samples at any one sampling time.



Figure 5.8:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the  $\text{NH}_4\text{NO}_3$  plots and three different rates.

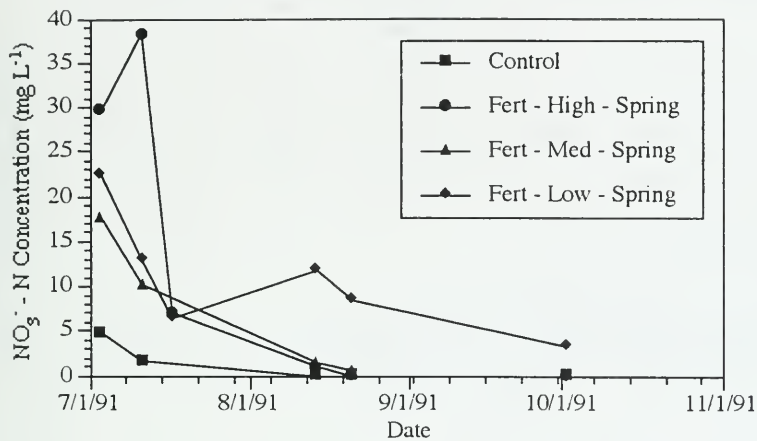


Figure 5.9:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the liquid cattle manure plots and three different rates.

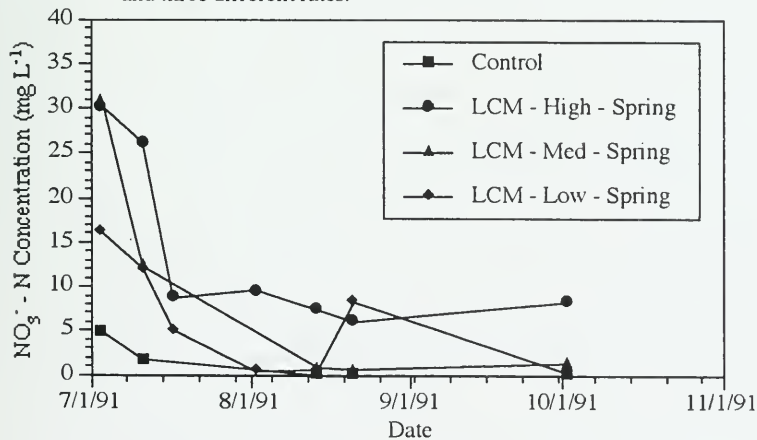


Figure 5.10:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the solid beef manure plots and three different rates.

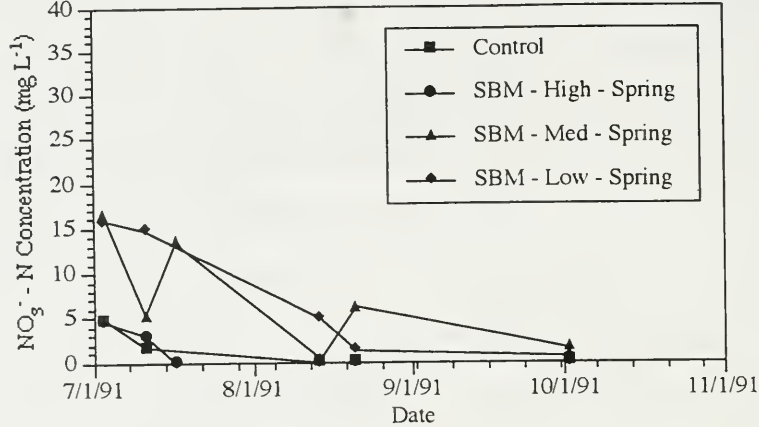


Figure 5.11:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the high N application rate plots and three different sources of N.

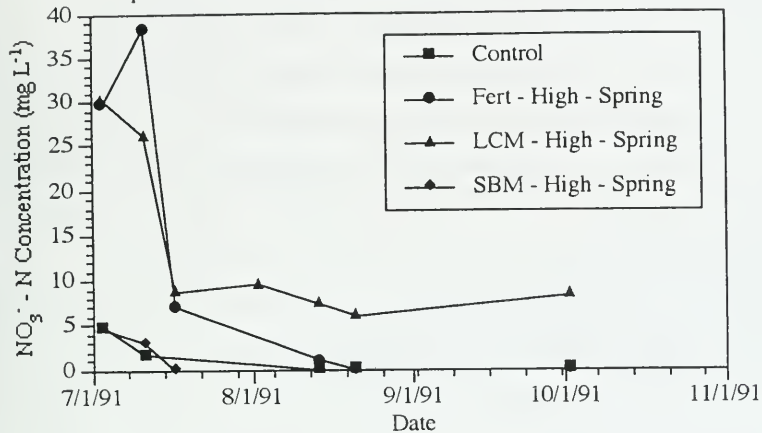


Figure 5.12:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the medium N application rate plots and three different sources of N.

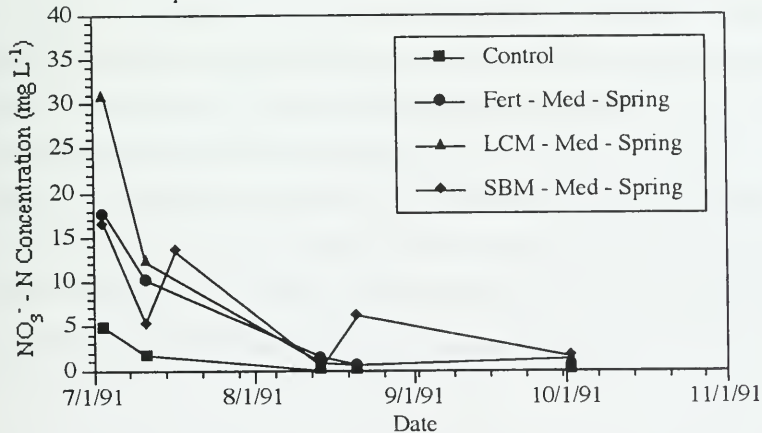
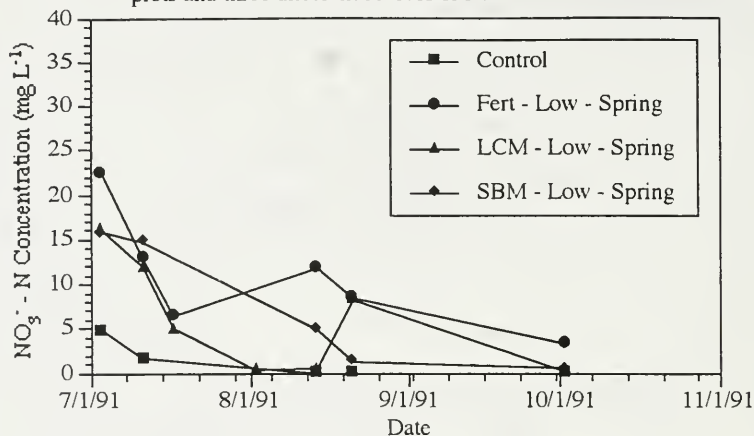


Figure 5.13:  $\text{NO}_3^-$  - N concentration over the 1991 growing season for the low N application rate plots and three different sources of N.



Figures 5.8 through 5.13 indicated that  $\text{NO}_3^-$  - N concentrations decreased over the growing season for all N sources and N application rates. In addition, the control plots had consistently lower concentrations than the other plots. Also, there was an indication that the various N sources had  $\text{NO}_3^-$  - N concentrations at any one time that were in the order of  $\text{NH}_4\text{NO}_3 = \text{LCM} > \text{SBM} = \text{Control}$ . This trend was similar to the trend observed in the 1991 yield data (Table 4.3). Again, this suggested that plants assimilated much of the available N in the SBM and control plots. In addition, immobilization of N and denitrification in the SBM plots could have accounted for the reduced yields and reduced  $\text{NO}_3^-$  - N concentrations leaving the root zone. Immobilization would have been less in the  $\text{NH}_4\text{NO}_3$  and LCM plots so that more N would have been available for plant assimilation and leaching.

Figures 5.8 through 5.13 also indicated a general trend of  $\text{NO}_3^-$  - N concentrations versus N application rate in the order of high > medium > low with respect to the  $\text{NH}_4\text{NO}_3$  and SBM N sources. However, this effect was not as obvious with the SBM source which suggested that N immobilization may be occurring at all the rates.

### 5.3.2 1992 Results

The 1992 solution sampler data included the effect of N application time. Table 5.4 gives the 1992 sampling dates and the ANOVA F values for each date. Ammonium concentrations are not presented for 1992 as the values remained low for each sampling date. Averaged over the sampling periods, N application time and N application rate,  $\text{NH}_4^+$  concentrations were 1.77, 2.13, 1.65 and 1.55  $\text{mg N L}^{-1}$  for the  $\text{NH}_4\text{NO}_3$ , SBM, LCM and Control treated plots, respectively.

Throughout 1992 and averaged over N application time and N application rate, the treated plots had significantly different  $\text{NO}_3^-$  - N concentrations which decreased in the order of FERT > LCM > SBM (Table 5.4). Fall treated plots had significantly higher  $\text{NO}_3^-$  - N concentrations than the spring treated plots up until the September 1992 when there was no longer any difference (Table 5.4). Significant differences were less obvious with regards to overall averaged N application rates (Table 5.4). In most cases, the high rate  $\text{NO}_3^-$  - N concentrations were significantly larger than the medium or low rates which were approximately equal. The N source with N application rate with N application time values will be used in various comparisons to indicate the relationships between treatments and the magnitude of  $\text{NO}_3^-$  - N concentrations that were measured (Figures 5.14 through 5.34).

In the legend of these figures, C is the control plots and the treated plots are referred to by their N source - N application rate - N application time treatments. N source is  $\text{NH}_4\text{NO}_3$  (F), solid beef manure (SBM) and liquid dairy cattle manure (LCM). The N application rates are high (H), medium (M) and low (L) and the N application times are spring (S) and fall (F). Thus the high rate of  $\text{NH}_4\text{NO}_3$  spring treated plots is denoted F-H-S.

Table 5.4: Summary of F values for the various treatments for the 1992 solution sample measured  $\text{NO}_3^-$  - N concentrations.

Date	Source of Variation							
	N Source	N Appl. Rate	N Appl. Time	Source*Rate*Time	Source*Rate	Source*Time	Rate*Time	
May 11	14.4**	4.4**	4.7**	NS	3.2**	NS	2.4*	
June 3	9.9**	NS	6.2**	NS	2.7**	NS	NS	
June 9	27.9**	NS	20.4***	NS	2.8**	3.0*	NS	
June 17	19.4**	6.6***	22.2**	2.1*	5.6***	10.7***	NS	
June 23	23.5**	NS	28.8**	NS	3.3**	7.9**	NS	
July 1	33.6**	4.3**	49.5**	3.1*	6.7**	13.3***	NS	
July 10	16.3**	2.9*	49.7**	4.3***	5.7**	7.5***	NS	
July 20	17.9**	3.7**	24.4***	NS	5.0***	3.3**	NS	
July 27	23.1**	4.7**	23.0**	NS	5.6***	4.3**	NS	
August 6	17.7**	NS	11.8**	NS	3.2**	NS	NS	
August 18	16.2**	NS	5.3**	NS	3.5**	NS	NS	
September 16	19.0**	NS	NS	3.4**	3.0**	5.1***	14.1***	
October 7	11.8**	2.6*	NS	NS	NS	2.9*	2.7*	

\* \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

Figure 5.14:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with high N rates in the spring.

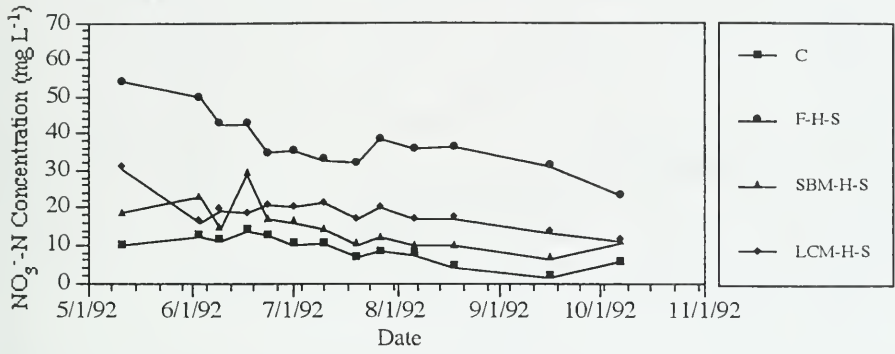


Figure 5.15:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with medium N rates in the spring.

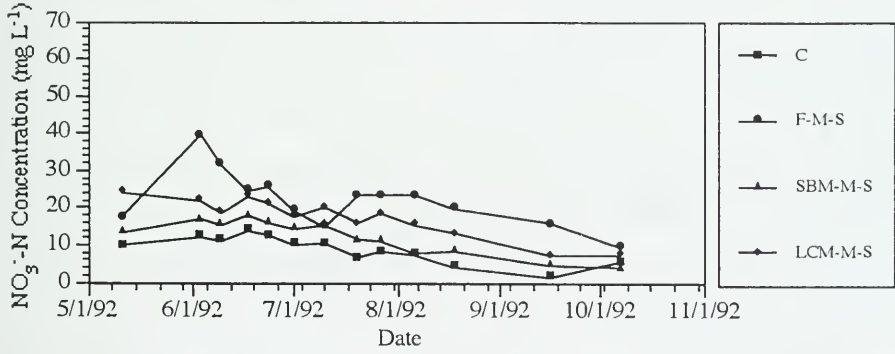


Figure 5.16:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with low N rates in the spring.

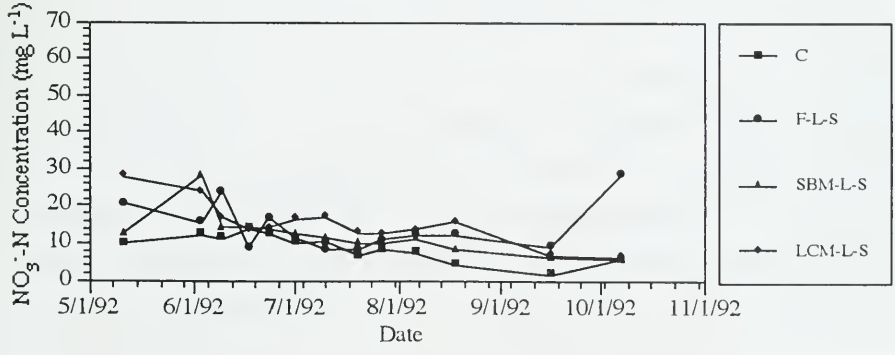


Figure 5.17:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with high N rates in the fall.

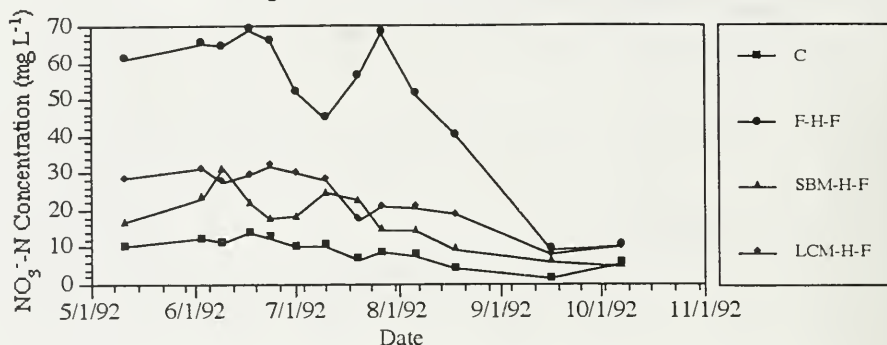


Figure 5.18:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with medium N rates in the fall.

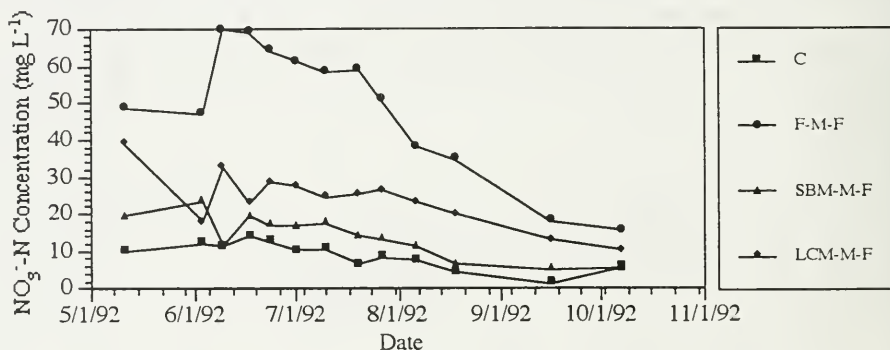
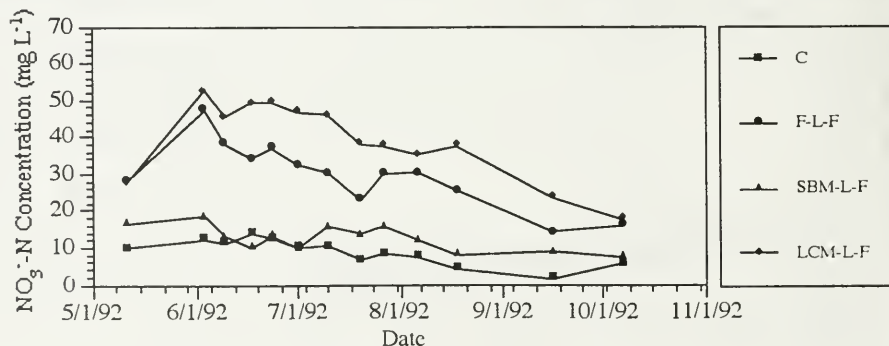


Figure 5.19:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the three N sources treated with low N rates in the fall.





The control plots averaged  $\text{NO}_3^-$  - N concentrations were approximately equal to the drinking water quality objective ( $10 \text{ mg N L}^{-1}$ ) at the beginning of the season but became less than the objective by the end of the growing season. The fact that the control plot  $\text{NO}_3^-$  - N concentrations are hovering around the  $10 \text{ mg N L}^{-1}$  value is important when considering cultivation of annual row crops and keeping the  $\text{NO}_3^-$  - N concentrations below the drinking water quality objective. In addition, all treated plots indicated a decrease in measured  $\text{NO}_3^-$  - N concentrations over the length of the growing season. This could be attributed to the large amount of July through August precipitation amounts (Figure 2.3) and the subsequent increase in soil water content ( $\approx 0.05 \text{ cm}^3 \text{ cm}^{-3}$ ) during these months (Figure 3.3).

All three N sources, applied in the spring, at each N rate had greater  $\text{NO}_3^-$  - N concentrations than were measured in the control plots (Figures 5.14 through 5.16). This was also observed with the fall treated plots (Figures 5.17 through 5.19). There was a consistent decreasing trend of  $\text{NO}_3^-$  - N concentrations in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . Again this was consistent at all N rates and both application times (Figures 5.14 through 5.19). However, this trend was most obvious at the high and medium rates, especially in the fall treated plots. This trend was attributed to the availability of  $\text{NO}_3^-$  - N in each source of manure. The  $\text{NO}_3^-$  from the  $\text{NH}_4\text{NO}_3$  source was available to be leached from the time of application. However, the LCM and SBM sources have negligible amounts of mineral  $\text{NO}_3^-$  - N when they are first applied (Table 2.4). The  $\text{NH}_4^+$  in both sources requires some time to be nitrified. The nitrification process does not occur all at once so that the  $\text{NO}_3^-$  is released slowly over time. In addition to this, the SBM source has even smaller amounts of available  $\text{NH}_4^+$  than the LCM source and requires even more time for the organic N to be mineralized. Thus the above mentioned trend in measured concentrations was expected. Also, lower concentrations would be expected in the SBM source as the higher C:N ratio of this type of manure would favour immobilization of available  $\text{NO}_3^-$  - N. It will also be suggested (Chapter 7) that increased denitrification losses from the SBM source would lead to lower  $\text{NO}_3^-$  - N concentrations in the leachate. The trend in concentrations between N sources was also consistent with the 1992 grain yield results (Table 4.7). It was shown that the yields followed the opposite

trend of  $\text{SBM} > \text{LCM} > \text{NH}_4\text{NO}_3$  which would be consistent with leaching losses in the order mentioned above.

Differences between the fall treated plots might be expected to be more obvious due to the leaching process at this site. Manures and fertilizer applied in the spring of 1992 would not be expected to reach the 80 cm depth until later in 1992. For example, the average soil water content was approximately  $0.33 \text{ cm}^3 \text{ cm}^{-3}$  (Appendix 1) from the time of the spring 1992 manure application (May 13, 1992; Table 4.5) to September 16, 1992. The net drainage during this time was approximately 10.88 cm (Appendix 4) which meant that the spring applied  $\text{NO}_3^- - \text{N}$  may have moved approximately 33 cm. Similar calculations suggest that by the October 7, 1992 sampling date the  $\text{NO}_3^- - \text{N}$  would only have moved to approximately the 37 cm depth. Similar calculations can be made for the amount of net drainage between the fall 1991 manure and fertilizer applications (October 7, 1991; Table 4.1) until May 1, 1992. Approximately 35 cm of net drainage occurred between these dates which would result in the  $\text{NO}_3^- - \text{N}$  moving to approximately the 105 cm depth. This is somewhat of an overestimate since runoff and snowpack sublimation were not considered. This demonstrates that the spring concentrations in Figures 5.14 through 5.34 are still being influenced by the spring 1991 manure and fertilizer applications and would be expected to remain lower than the fall treated plots throughout the 1992 sampling dates. In addition, the 1991 fall treated plots would be expected to be larger than the 1992 spring treated plots as they also received N applications in the spring of 1991 so as to preserve normal agronomic practices.

The  $\text{NO}_3^- - \text{N}$  concentration differences between N source and N rates are most obvious in the fall treated plots (Figures 5.23 through 5.25). The  $\text{NH}_4\text{NO}_3$  source had the largest difference between rates (Figure 5.23) and the SBM source had the smallest difference (Figure 5.24). The  $\text{NH}_4\text{NO}_3$  and LCM sources had  $\text{NO}_3^- - \text{N}$  concentrations that were well above the drinking water quality objective of  $10 \text{ mg N L}^{-1}$ . However, the SBM source's low and medium rates had concentrations that were slightly greater than the control plot's and were generally less than  $18 \text{ mg N L}^{-1}$ . It is important to remember, and, it will be shown (Chapter 6) that the SBM treated plots are increasing their soil organic matter and microbial populations over the length of the experiment.

This increase will eventually reach an equilibrium and mineralization will equal immobilization. At this point, it is likely that additions of SBM will produce larger  $\text{NO}_3^-$  - N concentrations than are being observed here.

The fall treated plots, for all N sources appear to indicate more of a change in  $\text{NO}_3^-$  - N concentrations than the spring plots (Figures 5.26 through 5.34). This was consistent with the net drainage information which indicated that  $\text{NO}_3^-$  - N concentrations, measured in 1992, were being influenced, to a greater extent, by the fall 1991 N applications than by the spring 1992 N applications. Spring and fall concentrations for all N sources and N rates became approximately equal by the October 7, 1992 sampling date but remained slightly larger than the control plot concentrations (Figures 5.26 through 5.34). Concentrations in spring treated plots may also have remained more uniform and lower throughout the growing season due to plant uptake. Plant uptake may in fact be responsible for keeping the concentrations in fall treated plots continually above the spring treated plots. This possibility will be examined with the 1993 solution sampler data as well as with the soil mineral N data (Chapter 6).

Figure 5.20:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with  $\text{NH}_4\text{NO}_3$  in the spring.

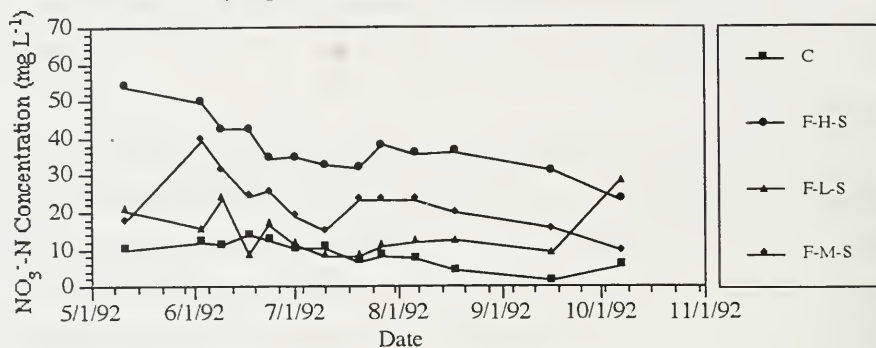


Figure 5.21:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with SBM in the spring.

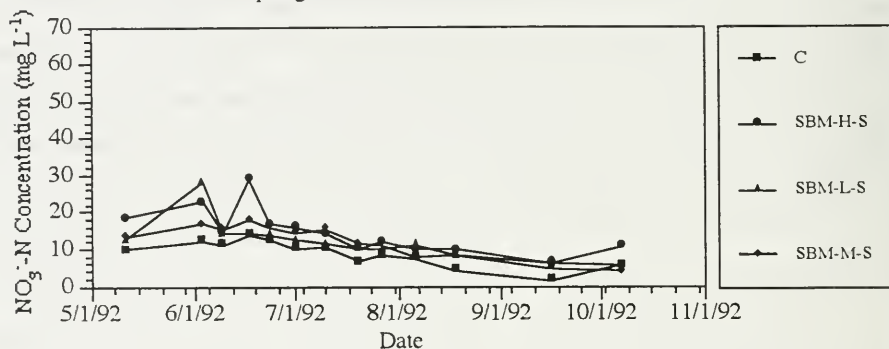


Figure 5.22:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with LCM in the spring.

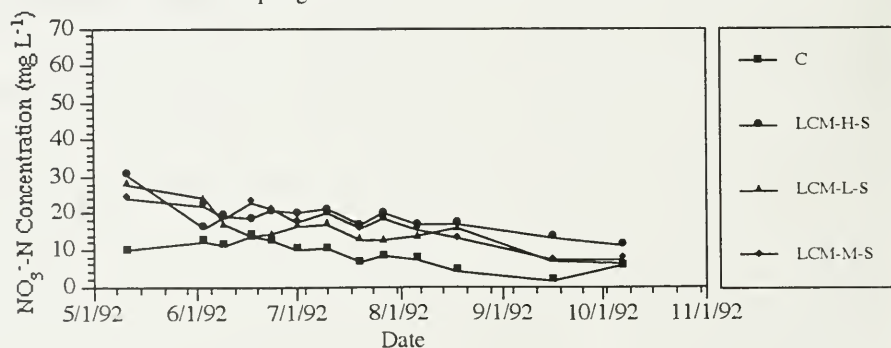


Figure 5.23:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with  $\text{NH}_4\text{NO}_3$  in the fall.

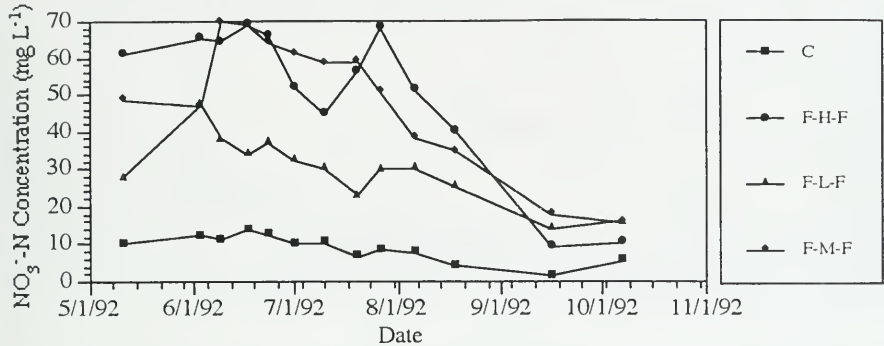


Figure 5.24:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with SBM in the fall.

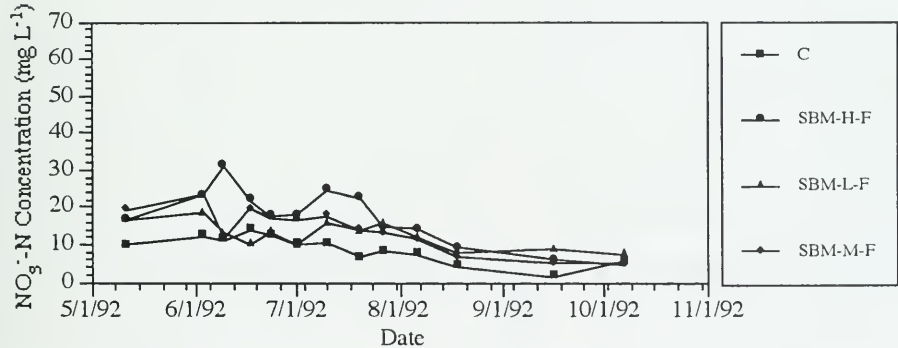


Figure 5.25:  $\text{NO}_3^-$ -N concentrations over the 1992 growing season for the three N rates treated with LCM in the fall.

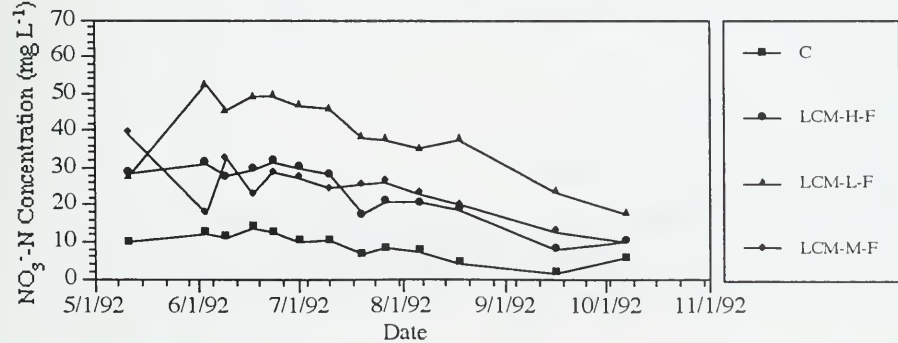


Figure 5.26:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with high rates of  $\text{NH}_4\text{NO}_3$ .

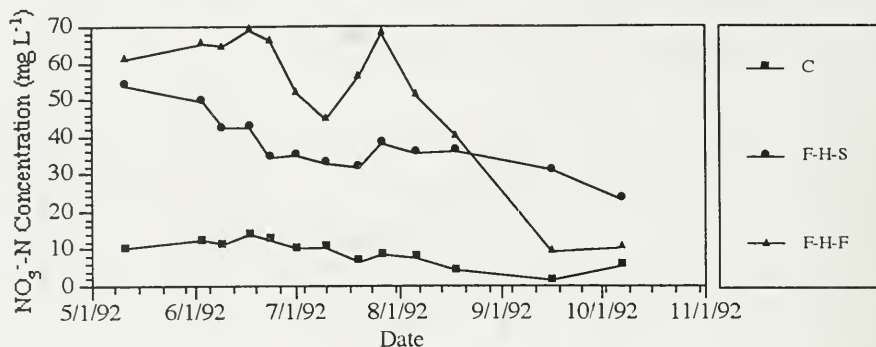


Figure 5.27:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with medium rates of  $\text{NH}_4\text{NO}_3$ .

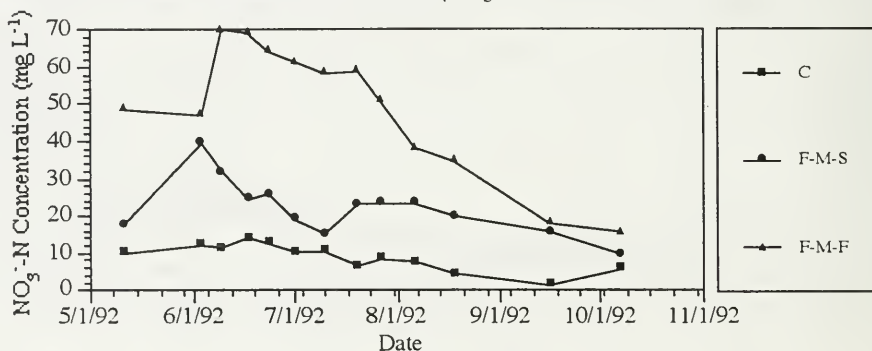


Figure 5.28:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with low rates of  $\text{NH}_4\text{NO}_3$ .

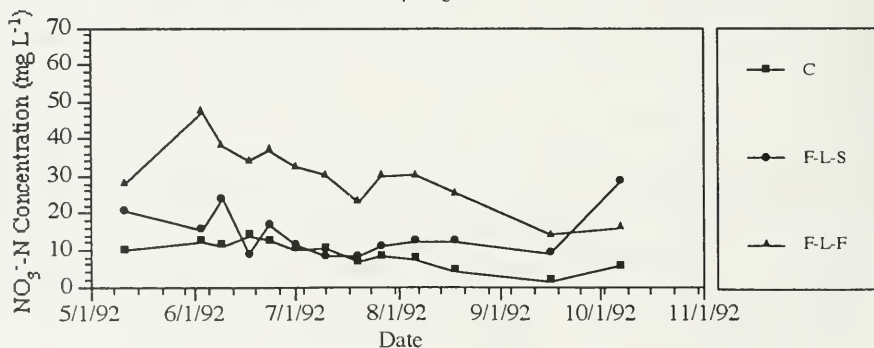


Figure 5.29:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with high rates of SBM.

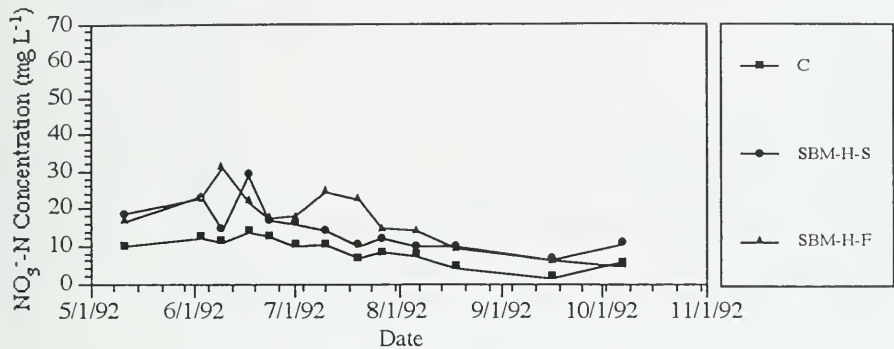


Figure 5.30:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with medium rates of SBM.

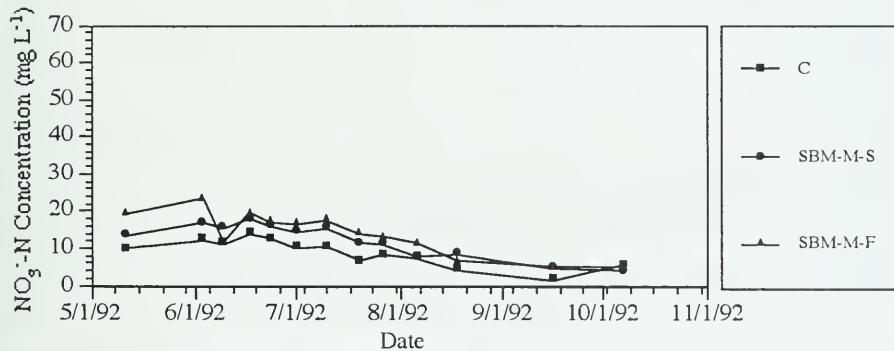


Figure 5.31:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with low rates of SBM.

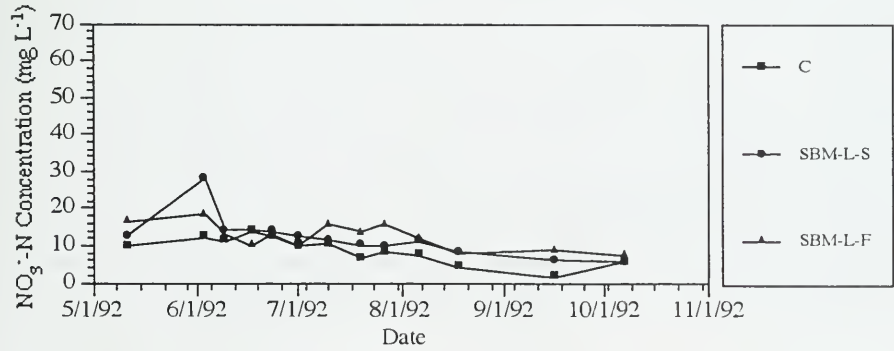




Figure 5.32:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with high rates of LCM.

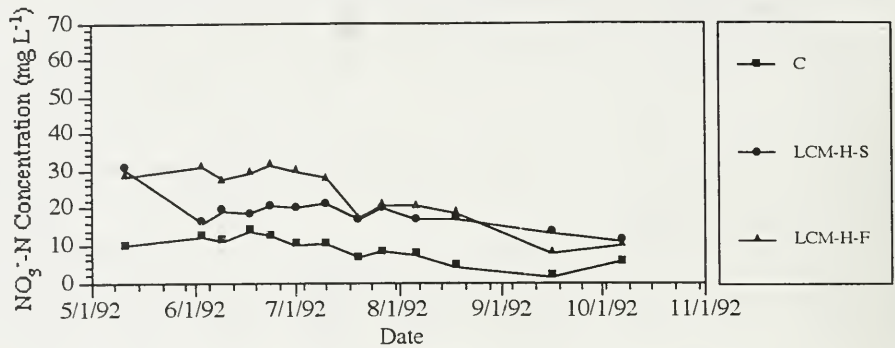


Figure 5.33:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with medium rates of LCM.

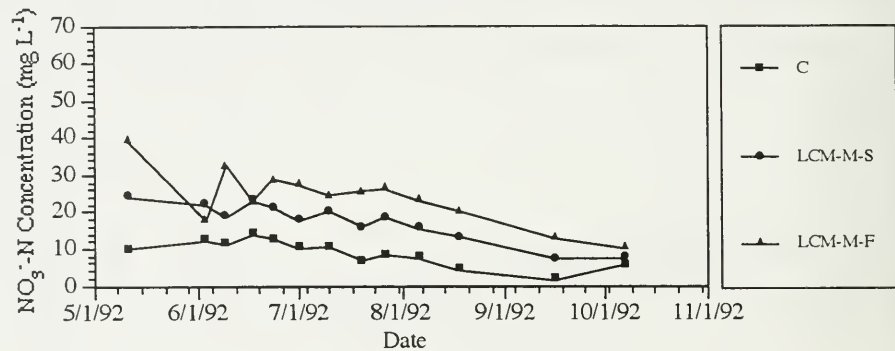
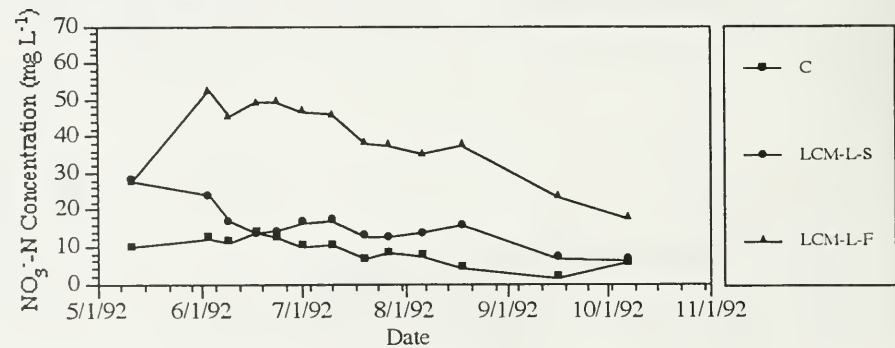


Figure 5.34:  $\text{NO}_3^-$  - N concentrations over the 1992 growing season for the two N application times treated with low rates of LCM.





### 5.3.3 1993 Results

The 1993 solution sampler measurements were similar to the 1992 measurements except that they were done over a longer time period and the samplers yielded an increased number and volume of samples. Table 5.5 gives the 1993 sampling dates and the ANOVA F values for each date. Ammonium concentrations are not presented for 1993 as the values remained low for each sampling date. Averaged over the sampling periods, N application time and N application rate,  $\text{NH}_4^+$  concentrations were 0.35, 0.43, 0.36 and 0.30  $\text{mg N L}^{-1}$  for the  $\text{NH}_4\text{NO}_3$ , SBM, LCM and Control treated plots, respectively. These measured concentrations were slightly lower than the 1992 measured values and still represent negligible losses of N.

Similar to 1992, a significant N source effect was observed at all sampling dates (Table 5.5). Again, when averaged over N application time and N application rate, the  $\text{NO}_3^-$  - N concentrations decreased in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . Unlike 1992, a significant N application rate effect was observed throughout the sampling period (Table 5.5).  $\text{NO}_3^-$  - N concentrations indicated a consistent trend which decreased in the order of high > medium > low. In addition, a consistent significant N application time effect was only observed in the April through July sampling dates where the fall treated plots had significantly higher  $\text{NO}_3^-$  - N concentrations than the spring treated plots. This trend became somewhat reversed later in the season but was not observed to be significant. There also appeared to be a reduced number of significant interactions in 1993 than in 1992 (Tables 5.4 and 5.5). The N source with N application rate with N application time values will be used in various comparisons to indicate the relationships between treatments and the magnitude of  $\text{NO}_3^-$  - N concentrations that were measured (Figures 5.35 through 5.55).

In the legend of these figures, C is the control plots and the treated plots are referred to by their N source - N application rate - N application time treatments. N source is  $\text{NH}_4\text{NO}_3$  (F), solid beef manure (SBM) and liquid dairy cattle manure (LCM). The N application rates are high (H), medium (M) and low (L) and the N application times are spring (S) and fall (F). Thus, the high rate of  $\text{NH}_4\text{NO}_3$  spring treated plots is denoted F-H-S.

Table 5.5: Summary of F values for the various treatments for the 1993 solution sample measured  $\text{NO}_3^-$  - N concentrations.

Date	Source of Variation					
	N Source	N Appl. Rate	N Appl. Time	Source*Rate*Time	Source*Rate	Source*Time Rate*Time
April 30	NS	5.2 <sup>**</sup>	9.6 <sup>***</sup>	NS	NS	NS
May 28	3.7 <sup>**</sup>	8.8 <sup>***</sup>	9.4 <sup>***</sup>	NS	3.4 <sup>**</sup>	NS
June 3	9.2 <sup>***</sup>	6.6 <sup>***</sup>	18.7 <sup>**</sup>	NS	3.0 <sup>**</sup>	NS
June 11	6.2 <sup>**</sup>	5.4 <sup>***</sup>	5.5 <sup>***</sup>	NS	2.2 <sup>*</sup>	NS
June 16	12.2 <sup>***</sup>	8.1 <sup>***</sup>	9.4 <sup>***</sup>	NS	6.1 <sup>***</sup>	NS
June 23	12.1 <sup>***</sup>	11.6 <sup>***</sup>	5.8 <sup>***</sup>	NS	3.5 <sup>*</sup>	NS
June 30	8.6 <sup>***</sup>	4.0 <sup>***</sup>	4.8 <sup>***</sup>	NS	2.2 <sup>*</sup>	NS
July 7	11.2 <sup>***</sup>	7.1 <sup>***</sup>	5.4 <sup>***</sup>	NS	3.4 <sup>**</sup>	NS
July 14	12.4 <sup>***</sup>	6.9 <sup>***</sup>	4.9 <sup>***</sup>	NS	NS	NS
July 21	10.7 <sup>***</sup>	4.0 <sup>***</sup>	4.8 <sup>***</sup>	NS	NS	NS
July 29	8.3 <sup>***</sup>	5.2 <sup>***</sup>	NS	NS	NS	NS
August 5	10.2 <sup>***</sup>	5.2 <sup>***</sup>	NS	NS	2.4 <sup>*</sup>	NS
August 11	7.6 <sup>***</sup>	5.5 <sup>***</sup>	NS	NS	NS	NS
August 18	5.9 <sup>***</sup>	9.4 <sup>***</sup>	NS	NS	NS	NS
August 27	10.0 <sup>***</sup>	10.6 <sup>***</sup>	NS	NS	2.8 <sup>*</sup>	NS
September 1	11.0 <sup>***</sup>	7.3 <sup>***</sup>	4.2 <sup>***</sup>	3.4 <sup>**</sup>	NS	NS
September 8	11.5 <sup>***</sup>	9.9 <sup>***</sup>	4.4 <sup>***</sup>	NS	NS	2.7 <sup>*</sup>
September 17	6.2 <sup>***</sup>	8.6 <sup>***</sup>	NS	2.2 <sup>*</sup>	NS	NS
September 22	7.6 <sup>***</sup>	10.9 <sup>***</sup>	NS	2.2 <sup>*</sup>	NS	NS
October 1	6.3 <sup>***</sup>	7.9 <sup>***</sup>	NS	NS	NS	NS
October 15	12.9 <sup>***</sup>	14.1 <sup>***</sup>	NS	2.1 <sup>*</sup>	NS	NS
October 22	8.5 <sup>***</sup>	16.8 <sup>***</sup>	NS	2.4 <sup>*</sup>	NS	NS
October 28	14.3 <sup>***</sup>	15.9 <sup>***</sup>	NS	2.2 <sup>*</sup>	NS	2.6 <sup>*</sup>
November 5	12.5 <sup>***</sup>	21.3 <sup>***</sup>	2.74 <sup>*</sup>	NS	NS	NS
November 12	16.0 <sup>***</sup>	14.4 <sup>***</sup>	NS	2.5 <sup>*</sup>	NS	NS
November 25	3.74 <sup>**</sup>	21.9 <sup>***</sup>	NS	NS	3.3 <sup>**</sup>	NS
December 14	13.8 <sup>***</sup>	28.1 <sup>***</sup>	NS	9.7 <sup>***</sup>	NS	3.9 <sup>**</sup>

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

Figure 5.35:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with high N rates in the spring.

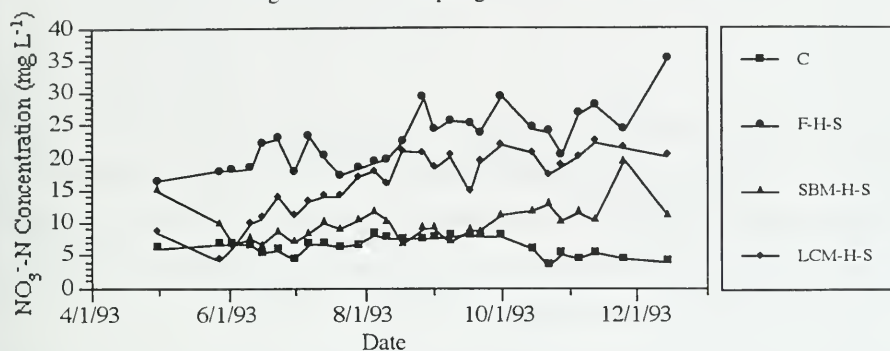


Figure 5.36:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with medium N rates in the spring.

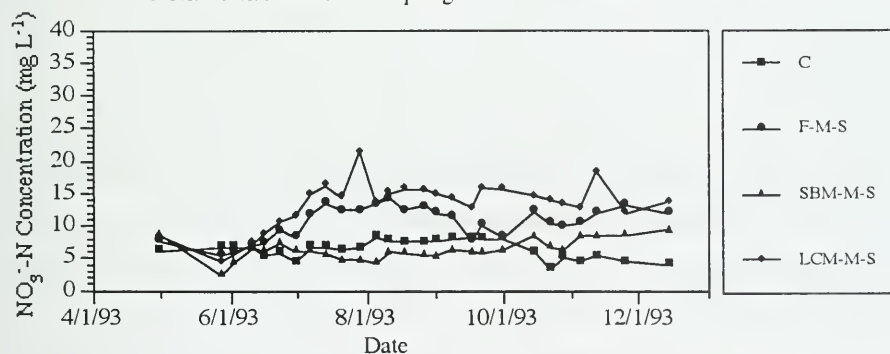


Figure 5.37:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with low N rates in the spring.

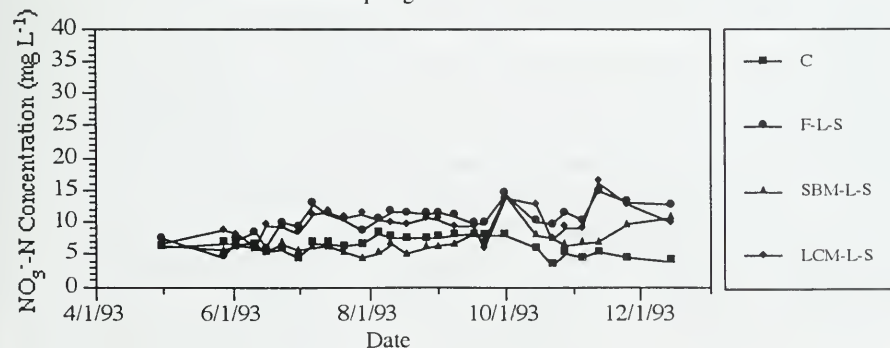


Figure 5.38:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with high N rates in the fall.

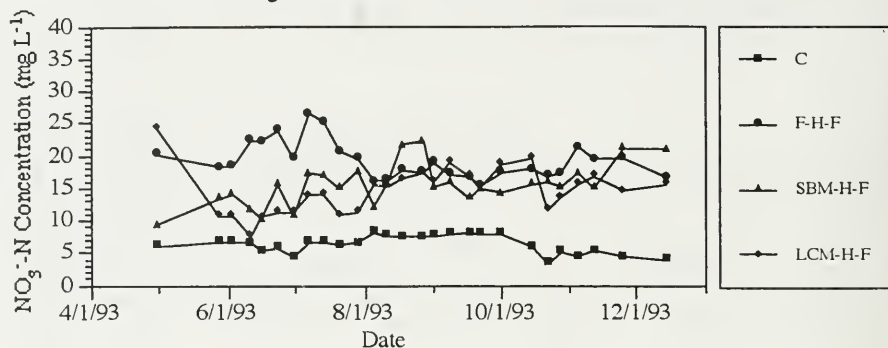


Figure 5.39:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with medium N rates in the fall.

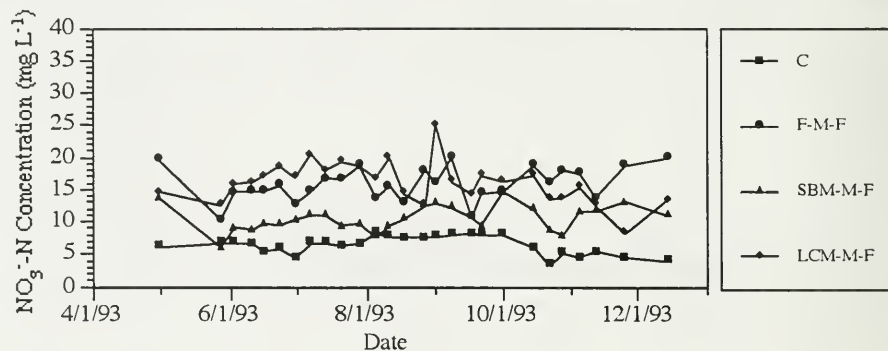
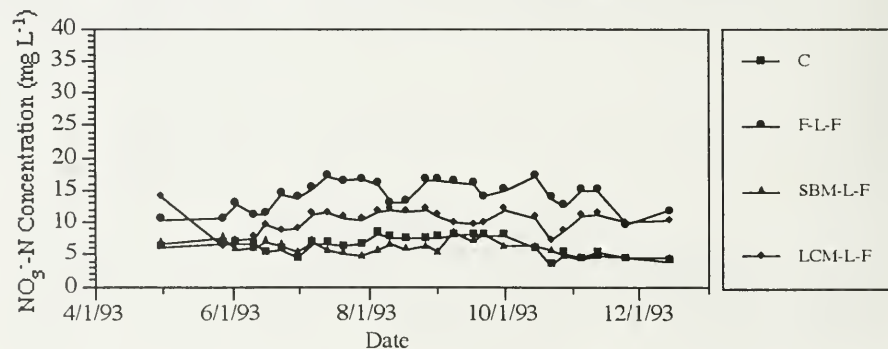


Figure 5.40:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N sources treated with low N rates in the fall.



The 1993 measured  $\text{NO}_3^-$  - N concentrations were consistently lower and appeared to be more variable than those measured in 1992. This was attributed to samples being taken more frequently and also to the soil water content of the soil profile. Since net drainage remained negative until the fall of 1993 (Figures 5.5 and 5.6; Appendix 4), the measured concentrations represented the  $\text{NO}_3^-$  - N that remained in the soil profile throughout the summer months. Since there was negligible drainage out of the root zone, the measured concentrations were a function of soil water content as well as the amount of  $\text{NO}_3^-$  - N in the soil profile. For example, many of the curves in Figures 5.35 through 5.55 indicated a gradual increase in concentration from the May through September sampling dates. This corresponds with a general decrease in soil water contents (Figure 3.4) over the same time. Similarly, concentrations appeared to be less variable in the October - November sampling dates when the soil water content remained more uniform.

The control plots had  $\text{NO}_3^-$  - N concentrations that remained below the drinking water quality objective throughout 1993. All N sources produced measured concentrations that were greater than the control plots and the drinking water quality objective except for the medium and low rates of the SBM source (Figures 5.35 through 5.40). This was consistent for both the fall and spring treated plots. As in 1992, there was a consistent trend of decreasing concentrations, as a function of N source, in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . This trend was more obvious in the spring treated plots and in the high and medium N rate treated plots.

There was a consistent trend of decreasing  $\text{NO}_3^-$  - N concentrations in the order of high > medium > low. This was consistent for both the fall and spring N application times (Figures 5.41 through 5.46, Table 5.5). As in 1992, the differences between rates were smallest for the SBM source as the high SBM spring treated plots yielded concentrations slightly above the drinking water quality objective while the medium and low SBM spring treated plots were below the 10 mg N L<sup>-1</sup> limit.

Differences between N application times were not as obvious as in 1992 and appeared to change depending on source and rate, especially in the latter half of 1993 (Table 5.5, Figures 5.47 through 5.55). The high N rate of  $\text{NH}_4\text{NO}_3$  applied in the spring remained higher than the

corresponding fall treated plots (Figure 5.47). This was reversed for the medium and low N rates (Figures 5.48 and 5.49). The LCM treated plots had negligible differences between N application times, especially in the latter half of 1993 (Figures 5.53 through 5.55). The high N rate of SBM applied in the fall remained higher than the corresponding spring treated plots but the reverse was true for the medium rate treated plots (Figures 5.50 and 5.51). There was no difference at the low rate of SBM treated plots except towards the last few sampling dates where the spring concentrations became larger than the fall concentrations (Figure 5.22).

In general, the spring treated plots were greater than or approximately the same as the fall treated plots by the December 14, 1993 sampling date. This suggested that the fall, 1992 applications of  $\text{NO}_3^-$  - N had moved closer to or past the 80 cm depth by the spring of 1993. The fact that net drainage remained negative throughout the summer of 1993 suggested that the spring  $\text{NO}_3^-$  - N applications would not have reached the 80 cm depth. These facts are consistent with the grain yield and grain N concentration measurements which found the spring treated plots to be greater than the fall treated plots (Tables 4.13 and 4.14). The  $\text{Cl}^-$  experiments also indicated that spring applied chemicals would not be expected at the 80 cm depth until late in the fall of 1993 (Table 5.6).

Figure 5.41:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the three N rates treated with  $\text{NH}_4\text{NO}_3$  in the spring.

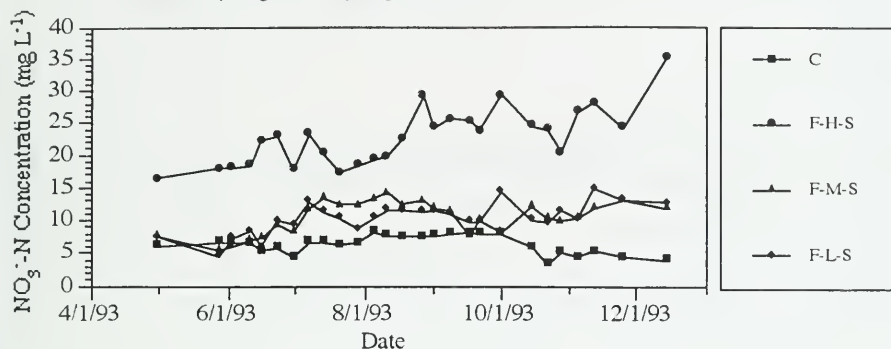


Figure 5.42:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the three N rates treated with SBM in the spring.

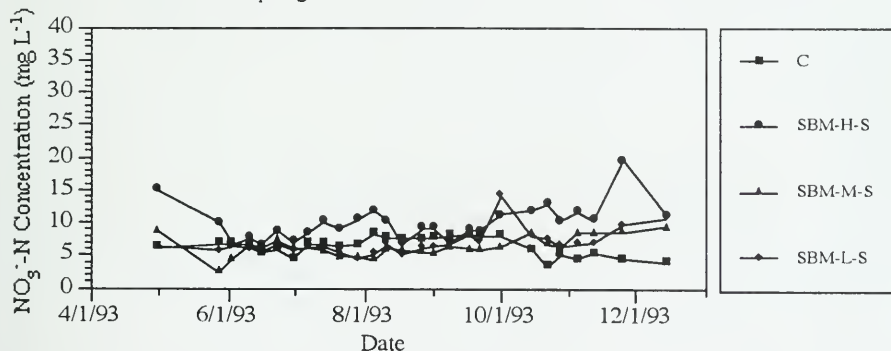


Figure 5.43:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the three N rates treated with LCM in the spring.

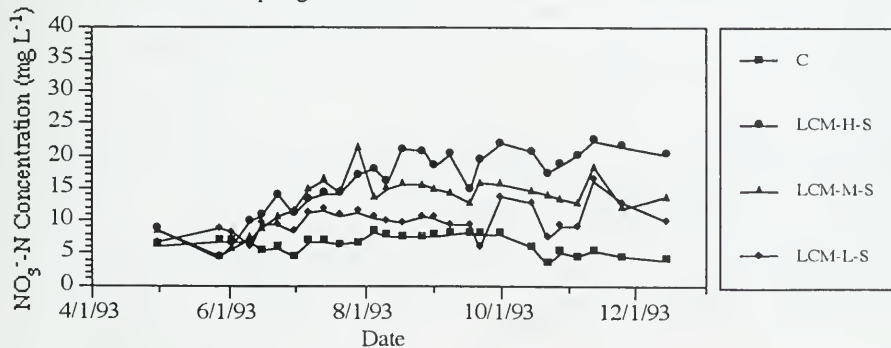




Figure 5.44:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N rates treated with  $\text{NH}_4\text{NO}_3$  in the fall.

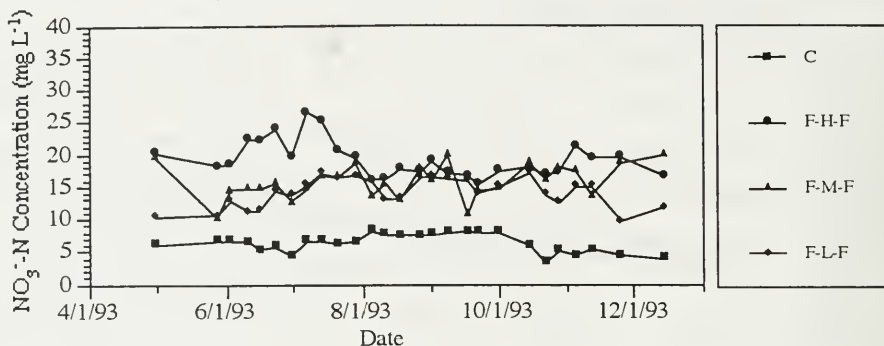


Figure 5.45:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N rates treated with SBM in the fall.

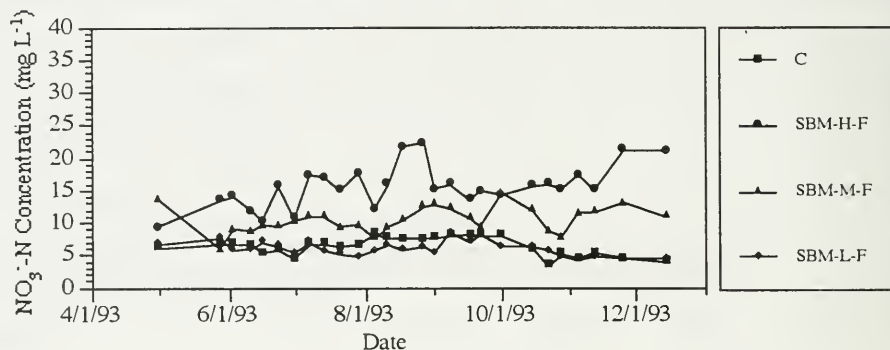


Figure 5.46:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the three N rates treated with LCM in the fall.

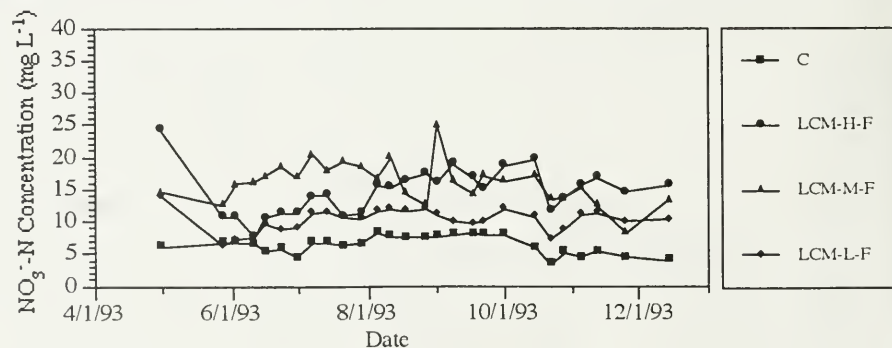




Figure 5.47:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the two N application times treated with high rates of  $\text{NH}_4\text{NO}_3$ .

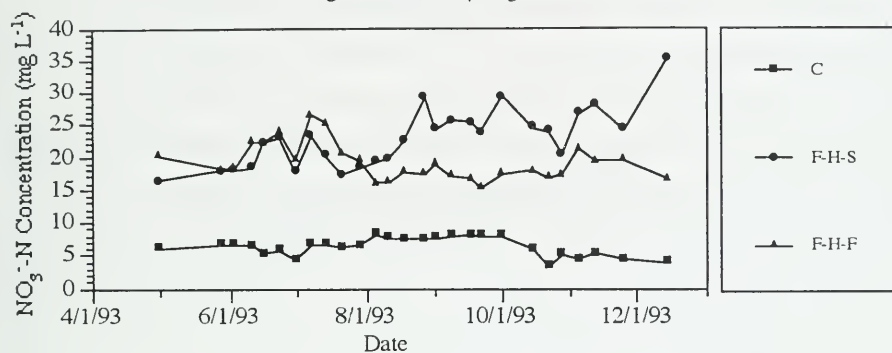


Figure 5.48:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the two N application times treated with medium rates of  $\text{NH}_4\text{NO}_3$ .

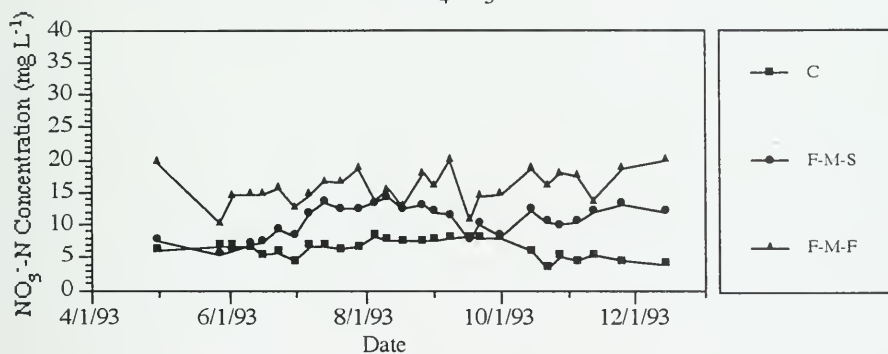
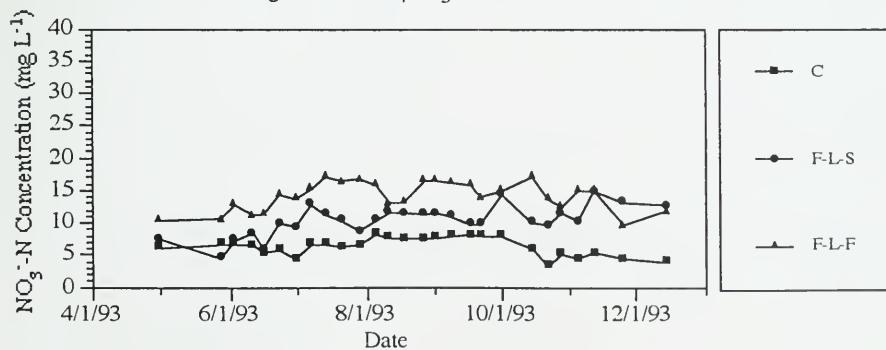


Figure 5.49:  $\text{NO}_3^-$ -N concentrations over the 1993 growing season for the two N application times treated with high low of  $\text{NH}_4\text{NO}_3$ .



The fall treated plots, for all N sources appear to indicate more of a change in  $\text{NO}_3^-$  - N concentrations than the spring plots (Figures 5.26 through 5.34). This was consistent with the net drainage information which indicated that  $\text{NO}_3^-$  - N concentrations, measured in 1992, were being influenced, to a greater extent, by the fall 1991 N applications than by the spring 1992 N applications. Spring and fall concentrations for all N sources and N rates became approximately equal by the October 7, 1992 sampling date but remained slightly larger than the control plot concentrations (Figures 5.26 through 5.34). Concentrations in spring treated plots may also have remained more uniform and lower throughout the growing season due to plant uptake. Plant uptake may in fact be responsible for keeping the concentrations in fall treated plots continually above the spring treated plots.

Figure 5.50:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with high rates of SBM.

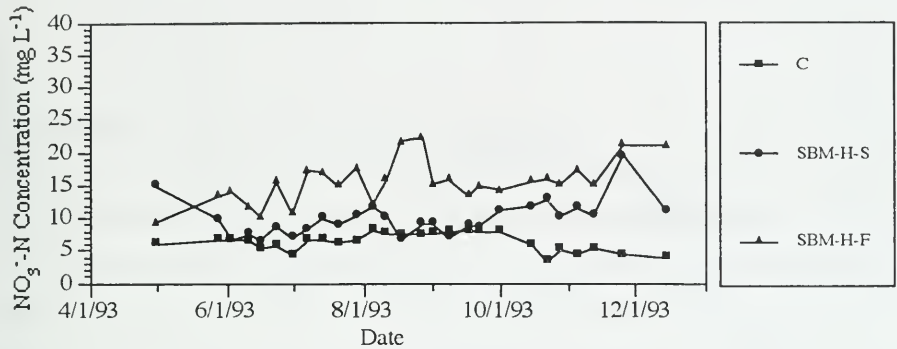


Figure 5.51:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with medium rates of SBM.

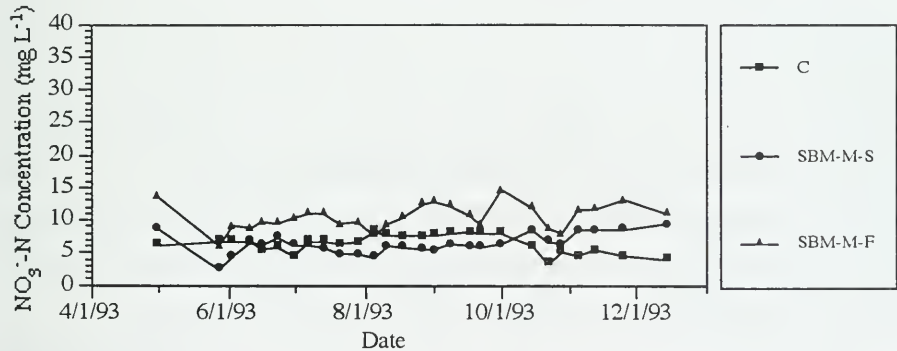


Figure 5.52:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with low rates of SBM.

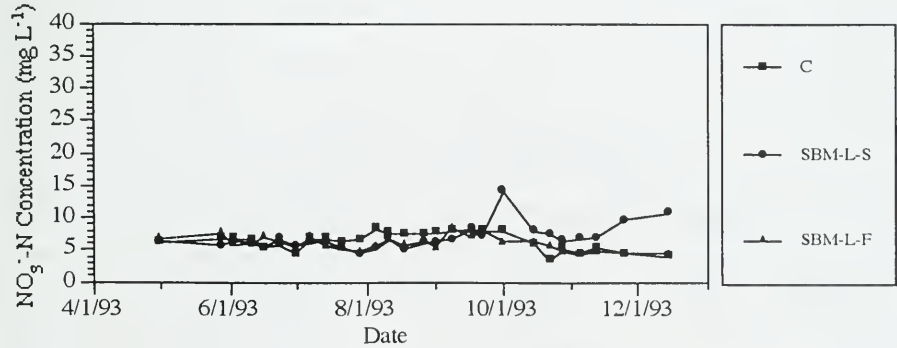


Figure 5.53:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with high rates of LCM.

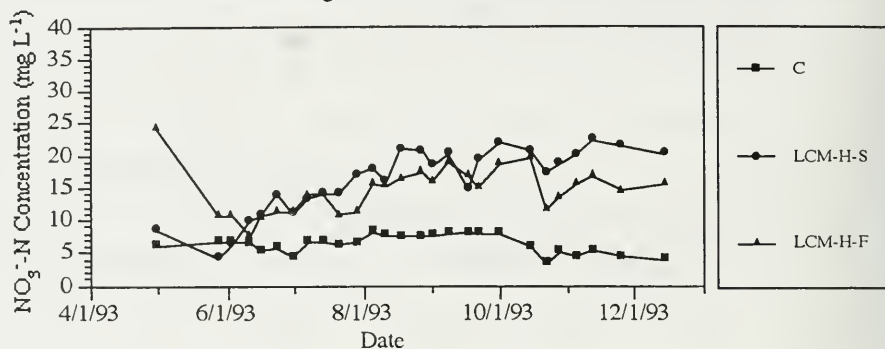


Figure 5.54:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with medium rates of LCM.

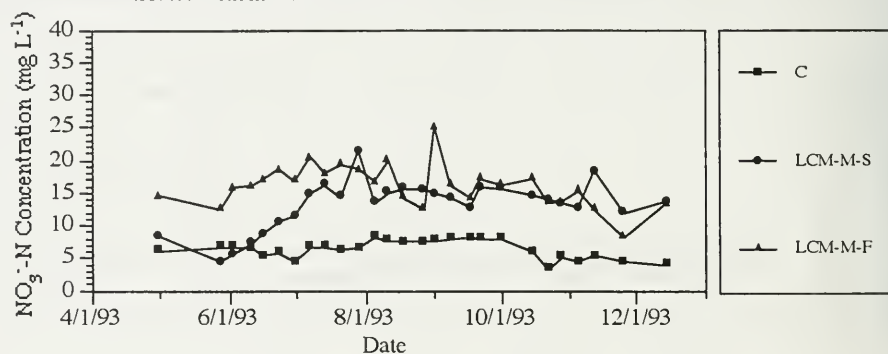
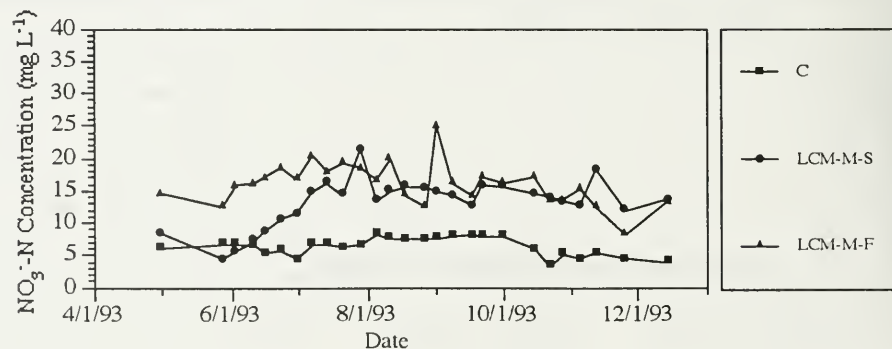


Figure 5.55:  $\text{NO}_3^-$  - N concentrations over the 1993 growing season for the two N application times treated with low rates of LCM.



#### 5.3.4 Nitrogen Leaching

In addition to the soil solution concentrations of  $\text{NO}_3^-$  - N, nitrogen leaching differences can also be summarized on a mass loss basis by combining the measured solution sampler concentrations with the calculated net water surplus / deficit values. Tables 5.6 and 5.7 give the net water surplus / deficit values and the monthly averaged soil solution concentrations of  $\text{NO}_3^-$  - N measured in 1992 and 1993, respectively. Note that the 1993 data also includes the final solution samples obtained on April 8, 1994 (Table 5.7). The monthly net water surplus values were estimated using the water balance [Eq. 3.1] for each month. Multiplying the net water surplus (positive) values by the measured concentrations gives the total mass per area ( $\text{kg NO}_3^-$  - N  $\text{ha}^{-1}$ ) of  $\text{NO}_3^-$  - N lost via leaching (Tables 5.8 and 5.9). These values represent our best estimates for leaching losses of  $\text{NO}_3^-$  - N out of the root zone. The net water deficit values (negative) were considered to be 0 as movement of water from the water table to the soil surface was considered negligible and therefore the corresponding mass losses of  $\text{NO}_3^-$  - N are also 0 (Tables 5.8 and 5.9). Note that the net water surplus over the winter months was calculated based on the assumption that all precipitation eventually infiltrated into the soil, evapotranspiration was 0 and the soil was at field capacity throughout this period ( $\Delta S = 0$ ). The 1991 data is not discussed here as it was the first year of the study and it was felt that the various treatments did not have enough time to exhibit large enough differences.

Tables 5.8 and 5.9 indicated similar differences to the measured solution sampler concentrations (sections 5.3.2 and 5.3.3). However, the differences reported are more meaningful due to the fact that measured differences in solution sampler concentrations are not important if there is a net deficit at the time of sampling (ie. no leaching). All treated plots had greater losses than the control plots. On average, the N sources had decreasing losses of N in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . On average, the N application rates had decreasing losses of N in the order of high > medium > low and fall treated plots had larger losses than spring treated plots. This was consistent with the results from the  $\text{Cl}^-$  leaching experiments. Note that this trend was not as obvious with the 1993-1994 data as no N sources were applied in the fall of 1993. 1992 had larger

Table 5.6: Monthly net water surplus / deficit and average  $\text{NO}_3^-$  - N concentrations for 1992.

Date	Net Surplus / Deficit (cm)	Average Monthly Concentrations of NO <sub>3</sub> - N for various Treatments (mg N L <sup>-1</sup> )																		NH <sub>4</sub> NO <sub>3</sub> Fertilizer					
		Control	Solid Reef Manure						Liquid Dairy Cattle Manure																
			Fall			Spring			Fall			Spring													
			Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High								
01/92	6.72	10	18	21	19	19	15	20	35	30	30	25	22.5	25	35	48	63	18	25	51.5					
02/92	2.73	10	18	21	19	19	15	20	35	30	30	25	22.5	25	35	48	63	18	25	51.5					
03/92	1.86	10	18	21	19	19	15	20	35	30	30	25	22.5	25	35	48	63	18	25	51.5					
04/92	7.52	10	18	21	19	19	15	20	35	30	30	25	22.5	25	35	48	63	18	25	51.5					
05/92	-1.56	10	18	21	19	19	15	20	35	30	30	25	22.5	25	35	48	63	18	25	51.5					
06/92	0.11	11.5	12	18	22	14	17	19.5	50	27.5	30	17.5	22	20	39	66	66	16.5	30.5	42.5					
07/92	3.69	9	14	16	20.5	10.5	14	14	42	25	25	14	18	19	31	60	57.5	10.5	21	35					
08/92	12.64	6	10.5	11	12	10	10	10	35	21	20	15	15	19	22.5	45	45	10.5	20.5	33.5					
09/92	-1.72	5	8	6	8	6	5	10	22	12.5	12.5	7.5	16	15	19	22	18	18	17.5	28					
10/92	4.71	5.2	7.6	7	8.2	6	5.5	11	21	13	14.5	7.25	15	15	18	21.75	18.5	16	15.5	26					
11/92	15.76	5.4	7.2	8	8.4	6	6	12	20	13.5	16.5	7	14	15	17	21.5	19	14	13.5	24					
12/92	5.88	5.6	6.8	9	8.6	6	6.5	13	19	14	18.5	6.75	12	15	16	21.25	19.5	12	11.5	22					
1992 Total																				61.62					

Table 5.7: Monthly net water surplus / deficit and average NO<sub>3</sub> - N concentrations for 1993-1994.

Date	Net Surplus/ Deficit (cm)	Average Monthly Concentrations of NO <sub>3</sub> - N for various Treatments (mg N L <sup>-1</sup> )															
		Solid Beef Manure								Liquid Dairy Cattle Manure							
		Fall				Spring				Fall				Spring			
		Low	Med	High	Control	Low	Med	High		Low	Med	High		Low	Med	High	
01/93	11.48	5.8	6.4	10	8.8	6	7	14	18	14.5	20.5	6.5	10	15	21	20	9.5
02/93	2.54	6	6	11	9	6	7.5	14	17	15	22.5	6.25	9	15	13	20.75	7.5
03/93	.74	6	6	13	9	6	8	15	15	15	25	6	8	15	11	20.25	6.5
04/93	8.66	6	6	15	9	6	8	15	14	15	25	6	7	15	10	20	6
05/93	-7.48	6	6	10	12	5	5	11	10	14	17.5	6	6	13	10	15	6
06/93	5.33	7	7	9	14	5	7	7	9	16	11	8	8	11	12.5	22	7
07/93	-1.24	7	7	10	15	5	5	9	11	17.5	13	10	15	15	16	23	11
08/93	-2.42	7.5	6	11	17.5	5.5	6	9	12	17	17	10	16	17.5	15.5	15	13
09/93	1.64	8	7	12	15	6	6	8	11	16.5	17	10	14	20	15.5	17	10
10/93	1.48	5.5	5.5	12	16	9	7	12	10	15	17	9	14	21	15	16	11
11/93	3.44	5	5	11	17.5	8	8	15	10	12	17	12	15	21	13	17.5	11
12/93	-1.40	4.5	4.5	11	21	10	8	15	9	14	17	10	13	21	11	20	12
01/94	7.60	4.7	4.7	11.25	20	10	8.5	14.5	9	14	17	10	13	21	11	19.25	13
02/94	2.40	4.9	4.9	11.5	19	10	9	14	9	14	16.5	10	13	21	11	18.5	12.5
03/94	4.70	5.1	5.3	11.75	18	10	9.5	14	9	14	16.25	11	13	21	11	17.75	12
04/94	11.90	5.29	5.57	12.5	17.5	9.5	9.5	13.5	9.25	14	16.25	11	13.1	21.2	11.5	17.5	12
Total	61.91																

Table 5.8: Monthly leaching losses of  $\text{NO}_3^-$  - N for 1992.

Date	Average Monthly Leaching Losses of NO <sub>3</sub> - N for various Treatments (kg N ha <sup>-1</sup> )																		
	Control	Solid Beef Manure						Liquid Dairy Cattle Manure						NH <sub>4</sub> NO <sub>3</sub> Fertilizer					
		Fall			Spring			Fall			Spring			Fall			Spring		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
01/92	6.72	12.1	14.12	12.77	12.77	10.08	13.44	23.52	20.16	20.16	16.8	15.12	16.8	23.52	32.25	42.34	12.1	16.8	34.61
02/92	2.73	4.91	5.73	5.19	5.19	4.1	5.46	9.56	8.19	8.19	6.83	6.14	6.83	9.56	13.1	17.2	4.91	6.83	14.06
03/92	1.86	3.35	3.91	3.53	3.53	2.79	3.72	6.51	5.58	5.58	4.65	4.19	4.65	6.51	8.93	11.72	3.35	4.65	9.58
04/92	7.52	13.54	15.79	14.29	14.29	11.28	15.04	26.32	22.56	22.56	18.8	16.92	18.8	26.32	36.1	47.38	13.54	18.8	3.87
05/92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06/92	.13	0.13	0.20	0.24	0.15	0.19	0.21	0.55	0.30	0.33	0.19	0.24	0.22	0.43	0.73	0.73	0.18	0.34	0.47
07/92	3.32	5.17	5.90	7.56	3.87	5.17	5.17	15.50	9.23	9.23	5.17	6.64	7.01	11.44	22.14	21.22	3.87	7.75	12.92
08/92	7.58	13.27	13.90	15.17	12.64	12.64	12.64	44.24	26.54	25.28	18.96	18.96	24.02	28.44	56.88	56.88	13.27	25.91	42.34
09/92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10/92	2.45	3.58	3.30	3.86	2.83	2.59	5.18	9.89	6.12	6.83	3.41	7.07	7.07	8.48	10.24	8.71	7.54	7.3	12.2
11/92	8.51	11.35	12.61	13.24	9.46	9.46	18.91	31.52	21.28	26.00	11.03	22.06	23.64	26.79	33.39	29.9	22.06	21.28	37.82
12/92	3.29	4.00	5.29	5.06	3.53	3.82	7.64	11.17	8.23	10.88	3.97	7.06	8.82	9.4	12.5	11.4	7.06	6.76	12.94
Total	44.11	71.40	80.75	80.91	68.26	62.12	87.41	178.78	128.19	135.04	89.81	104.4	117.86	150.89	226.26	247.48	87.85	116.42	180.81



Table 5.9: Monthly leaching losses of NO<sub>3</sub> - N for 1993-1994 and average flux concentration for 01/92 - 04/94.

Date	Average Monthly Leaching Losses of NO <sub>3</sub> - N for various Treatments (kg N ha <sup>-1</sup> )												NH <sub>4</sub> NO <sub>3</sub> Fertilizer					
	Solid Beef Manure						Liquid Dairy Cattle Manure											
	Control			Fall			Spring			Fall			Spring			Fall		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
01/93	6.66	7.35	11.48	10.1	6.89	8.36	16.07	20.66	16.65	23.53	7.46	11.48	17.22	17.22	24.11	22.96	11.48	10.91
02/93	1.52	1.52	2.79	2.29	1.52	1.91	3.56	4.32	3.81	5.72	1.59	2.29	3.81	3.3	5.27	5.21	2.03	1.91
03/93	0.44	0.44	0.96	0.67	0.44	0.59	1.11	1.11	1.11	1.85	0.44	0.59	1.11	0.81	1.50	1.55	0.52	0.48
04/93	5.20	5.20	12.99	7.79	5.20	6.93	12.99	12.12	12.99	21.65	5.20	6.06	12.99	8.66	17.32	18.19	5.20	5.20
05/93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
06/93	3.73	3.73	4.80	7.46	2.67	3.73	3.73	4.78	8.53	5.86	4.26	4.26	5.86	6.66	7.73	11.73	4.26	3.73
07/93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
08/93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
09/93	1.31	1.15	1.97	2.46	0.98	0.98	1.31	1.80	2.71	2.79	1.64	2.30	3.28	2.54	2.46	2.79	1.64	1.64
10/93	0.81	0.81	1.78	2.37	1.33	1.04	1.78	1.48	2.22	2.52	1.33	2.07	3.11	2.22	2.37	2.66	1.63	1.48
11/93	1.72	1.72	3.78	6.02	2.75	2.75	5.16	3.44	4.13	5.85	4.13	5.16	7.22	4.47	6.02	6.88	4.47	3.78
12/93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01/94	3.57	3.57	8.55	15.20	7.60	6.46	11.00	6.84	10.64	12.92	7.60	9.88	15.96	8.36	14.63	13.87	9.88	9.50
02/94	1.18	1.18	2.76	4.56	2.40	2.16	3.36	2.16	3.36	3.96	2.40	3.12	5.04	2.64	4.44	4.44	3.00	3.12
03/94	2.40	2.49	5.52	8.46	4.70	4.47	6.58	4.23	6.58	7.64	5.17	6.11	9.87	5.17	8.34	8.93	5.64	6.11
04/94	6.30	6.63	14.87	20.83	11.31	11.31	16.07	11.01	16.67	19.34	13.09	15.59	25.23	13.69	20.29	23.21	14.28	15.47
1993 Total	21.39	21.92	40.55	39.16	21.78	26.29	45.71	49.71	52.15	69.77	26.05	34.21	54.60	45.88	66.78	71.97	31.23	29.13
10/93 - 04/94 Total	15.98	16.40	37.26	57.44	30.09	28.19	43.95	29.16	43.60	52.23	33.72	41.93	66.43	36.55	56.09	59.99	38.90	39.46
Avg Flux Conc.	6.39	8.68	12.39	13.69	9.39	9.26	13.77	20.46	17.61	20.13	11.67	14.03	18.50	18.35	27.58	29.94	12.30	14.55

losses than 1993 which was consistent with the above normal amount of precipitation in 1992. Also of interest is the fact that the leaching losses are approximately of the same magnitude as the denitrification losses (Table 7.3). In addition, the N source trend of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$  observed with the leaching losses is reversed for denitrification. It would appear that the major N loss for the  $\text{NH}_4\text{NO}_3$  source is via leaching while denitrification accounts for similar N losses as leaching in the manure sources.

This leaching data can also be compared with the changes in soil  $\text{NO}_3^-$  - N over a specific period. The changes in soil N (Chapter 6) occur mostly in the top 30 cm of the soil profile. The plots were sampled in late October 1993 and again on May 6, 1994 from the 0 - 30 cm depth. The amount of  $\text{NO}_3^-$  - N lost over this time was calculated to be 41.1, 18.5, 22.7 and 7.2 kg N ha<sup>-1</sup> for the plots treated in the spring with high rates of  $\text{NH}_4\text{NO}_3$ , LCM, SBM and the control plots, respectively. The corresponding losses calculated with the solution sampler and net water deficit / surplus data were 107.7, 66.4, 44.0 and 16.0 kg N ha<sup>-1</sup>, respectively. These losses were calculated using linearly interpolated concentrations between solution sampling dates and the monthly net water surplus from November 1993 through April 1994 (Tables 5.6 through 5.9). While the trend is similar between treatments, there remains a difference in magnitude between the two types of measurements. Reasons for the discrepancy include overestimation of net drainage as runoff and sublimation of the snowpack were assumed to be negligible. In addition, the May soil sampling would have included a large amount of recently mineralized N from soil organic matter which would have lessened the difference between the October 1993 and May 1994 soil sampling dates.

Additional information of N dynamics at this site was obtained via an <sup>15</sup>N experiment that was carried out on subplots established within several of the larger plots. A brief description of the experiment follows. On each replicate of the LCM plots that received medium rates of manure in the spring (Figure 2.4), a 2.5 x 5 m microplot was delineated. Immediately after the LCM was applied to the soil, 250 mL of a 1.0766M solution of ammonium sulphate containing <sup>15</sup>N at 99.2 atom percent. The manure was then incorporated using a manually operated rotary digger. The seedbed was prepared by hand forking to leave the surface in a form similar to that of the main plot.

The same procedure was adopted on the replicate plots of the treatment receiving the medium level of nitrogen fertilizer in the spring. However, on these microplots no other nitrogen fertilizer was applied in 1991, but the normal application for that treatment was applied in 1992. Planting of the microplots was done at the same time as the main plot.

Soil and plant samples were collected during the 1991 and 1992 seasons to follow the transfer of nitrogen from the mineral fraction of the manure into the crop, and to identify how much of this nitrogen was lost. The plots not receiving manure acted as checks to identify the fate of the mineral nitrogen present in the soil at planting in 1991.

In 1991, the average loss of the  $^{15}\text{N}$  from the manured plots was almost 25% (Table 5.10). This loss was potentially due to the combination of volatilization of ammoniacal nitrogen to the atmosphere, denitrification, and leaching of nitrate nitrogen below the rooting zone.

Table 5.10: The percentage of  $^{15}\text{N}$  in the plant and soil at harvest 1991, and the loss calculated as the difference between the amount added and the total recovered.

Component	Recovery of $^{15}\text{N}$ from Two Treatments (%)	
	LCM	Without Manure
Plant	$25.7 \pm 3.0$	$31.2 \pm 4.3$
Soil	$48.3 \pm 4.3$	$44.5 \pm 5.0$
Loss	$26.0 \pm 6.1$	$24.4 \pm 2.4$

Some  $14.8 \pm 1.9\%$  of the nitrogen in the crop was derived from the labelled mineral N in the manure, and was about one quarter of this fraction of the manure. Half of the  $^{15}\text{N}$  remained in the soil.

Where no manure had been applied, the uptake of  $^{15}\text{N}$  by the corn at harvest was not significantly different (31%) from that in manured plots, but results indicated that only  $3.6 \pm 0.5\%$  of N in the crop was derived from mineral N present in the soil at planting. In this case, over 96% of the N in the crop had been derived from N mineralized after this time. Uptake of  $^{15}\text{N}$  into the crop showed a similar pattern in plots treated with manure and without manure, although with the

exception of one sampling occasion, the average recovery from plots not receiving manure was greater than that from manured plots.

The loss of N from May 1991 to October 1992 was approximately 35% of the total applied (Table 5.11). The loss of  $^{15}\text{N}$  from manured and non-manured plots over the whole period from harvest 1991 to harvest 1992 was about 12% greater than the loss over the growing season in 1991. The average loss from plots without manure was about 15% in the second year, but the recoveries of  $^{15}\text{N}$  from the crop and soil were very similar to those from the manured plots.

Table 5.11: The percentage of  $^{15}\text{N}$  in the crops grown in 1991 and 1992, and in the soil after harvest 1992, and the loss calculated as the difference between the amount added and the total recovered.

Component	Recovery of $^{15}\text{N}$ from Two Treatments in 1991 and 1992 (%)	
	LCM	Without Manure
Plant	31.6 $\pm$ 4.4	34.3 $\pm$ 4.7
Soil	33.1 $\pm$ 3.7	26.4 $\pm$ 1.97
Loss	35.2 $\pm$ 7.9	39.3 $\pm$ 5.2

The potential for denitrification was greater in the manured plots than in plots receiving only mineral N because of the C addition. In this experiment, the losses from the two treatments were similar. This suggests that most losses were due to the other mechanisms. Losses due to volatilization would be expected to be greatest during the application of the manure (and  $^{15}\text{N}$ ). Total loss in 1992 was half that of the previous season, so the results suggest an important loss mechanism. The suggestion of a greater recovery of  $^{15}\text{N}$  in the crop not receiving manure would also support the suggestion of a significant loss by volatilization. The smallest loss from a manured plot recorded in 1991 was 8.7% of the  $^{15}\text{N}$  applied. If this represents the loss by volatilization alone, then total leaching loss over the whole experiment could have been as high as 30%, and the latter would then be the most important loss mechanism. Again, these results are consistent with previous results (denitrification, leaching) that indicated that leaching is an important

loss mechanism on the LCM plots and especially on the  $\text{NH}_4\text{NO}_3$  treated plots. Leaching and denitrification appear to be important N loss mechanisms on the SBM treated plots.

### 5.3.5 Summary

The 1991 solution sampler data was limited by the reduced number of sampling dates and sample volumes but indicated similar trends as were observed in 1992 and 1993. Measurements were made between May and October and April through December in 1992 and 1993, respectively. In general,  $\text{NH}_4^+$  concentrations were below  $2 \text{ mg N L}^{-1}$  when averaged over sampling dates, N application rates and N application times. Measured  $\text{NO}_3^-$  - N concentrations were observed to be a function of the soil water content as well as the other treatments. The measured  $\text{NO}_3^-$  - N concentrations in the control plots remained below the drinking water quality objective of  $10 \text{ mg N L}^{-1}$  in all three years. All treated plots except those treated with low N application rates of the SBM source (spring and fall) remained above the  $10 \text{ mg N L}^{-1}$  limit.

Each year had a significant N source effect with decreasing  $\text{NO}_3^-$  - N concentrations in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . This was attributed to the availability of  $\text{NO}_3^-$  - N from the various sources. The  $\text{NO}_3^-$  from the  $\text{NH}_4\text{NO}_3$  was available for leaching if plant uptake, microbial immobilization or denitrification were negligible whereas the  $\text{NO}_3^-$  in the manure sources was not as available. Mineralization and nitrification require time and release the N slowly which may have produced the lower concentrations. In addition, denitrification losses will be shown to follow a consistent decreasing trend of  $\text{SBM} > \text{LCM} > \text{NH}_4\text{NO}_3$  (Chapter 7). Although the SBM source had the lowest measured concentrations, it should be noted that the microbial biomass and soil organic matter levels were most likely still increasing to a higher equilibrium. It is not known how many manure applications are needed to reach this equilibrium but once the level is reached, it is probable that  $\text{NO}_3^-$  - N losses may dramatically increase from this source due to mineralization.

All three years indicated a consistent trend of decreasing  $\text{NO}_3^-$  - N concentrations, from N application rates, in the order of high > medium > low. The  $\text{NH}_4\text{NO}_3$  indicated the largest difference between N application rates followed by the LCM and SBM sources. In most cases

there was less than a  $10 \text{ mg N L}^{-1}$  difference between the high and low SBM treated plots on any given sampling date.

Due to a lack of positive net drainage during the growing season, the fall treated plots tend to have larger  $\text{NO}_3^- - \text{N}$  concentrations than the spring treated plots when measured during the growing season. This effect was shown to decrease over the length of the growing season until the spring treated plots were approximately equal to or slightly greater than the fall treated plots. This was attributed to the  $\text{NO}_3^- - \text{N}$  from the fall treated plots having moved closer to or past the 80 cm depth over the previous fall / spring leaching period. In addition, increased plant uptake of N from the spring treated plots would keep concentrations lower. The increased plant uptake was consistent with the measured yields and N concentrations. Also, any  $\text{NO}_3^- - \text{N}$  available for leaching in the spring treated plots would not appear at the 80 cm depth until late in the fall after it was applied.



## Chapter 6 Soil Mineral N, $\text{CHCl}_3$ -Extractable N and C

### 6.1 Introduction

The mineralization of organic nitrogen is a major source of mineral N available to plants even in soils amended with inorganic N fertilizer. The dynamic exchange between mineralization of labile organic N sources, catalyzed by the soil microflora, and the immobilization of inorganic N as a result of biosynthesis influences the concentration of inorganic N accumulating in the soil. The accumulation of inorganic N is major determinant of the potential N lost from the system via volatilization, denitrification or leaching. The balance between N mineralization and immobilization is determined by the amount and C/N ratio of organic compounds added to the soil. Manures can differ dramatically in the relative concentrations of C and N contained in the organic N fraction and as a result influence the potential for mineral N accumulation in the soil. An understanding of the impact of land application of organic amendments such as manure, and the potential for the conservation of N in the soil horizon, requires an evaluation of the interchange of inorganic N between dynamic organic N fractions and the mineral N fraction ( $\text{NH}_4^+$ ,  $\text{NO}_2^-$  and  $\text{NO}_3^-$ ).

The quantification of labile organic N in soil is complicated by the wide range of compounds and their complexity. Exposure of soil to chloroform ( $\text{CHCl}_3$ ) results in the rupture of microbial cell walls and the release of organic compounds associated with the microbial biomass (Jenkinson and Powlson, 1976), a highly labile organic fraction in soil (Bonde et al., 1988; Carter and MacLeod, 1987; Roberston et al., 1988). Measurement of the microbial biomass ( $\text{CHCl}_3$ -labile) C, N, P and S has been shown to be indicative of labile organic fractions of these nutrients and indicative of management impacts on soil productivity (Bolton et al., 1985; Carter, 1986; Dalal and Meyer, 1987). The proportion of the biomass extracted or mineralized following exposure to  $\text{CHCl}_3$  ( $k_C$ ,  $k_N$ ,  $k_P$  or  $k_S$ ) has been found to be relatively constant across a wide range of soils although precise determination of the proportionality constant on individual samples has been recommended (Voroney and Paul, 1984; Azam et al., 1988; Bremer and van Kessel, 1990). Precise determination of the size of the microbial biomass requires an evaluation of this proportionality

constant. In the current work, the amount of  $\text{CHCl}_3$ -labile organic C and N were measured to assess the impact of manure addition of the size of labile organic C and N fractions in the soil. In the absence of precise determinations of the proportionality constant, the values are expressed as  $\text{CHCl}_3$ -labile organic C or  $\text{CHCl}_3$ -labile total N. In general terms the  $\text{CHCl}_3$ -labile fraction represents 25% of the biomass C and 18% of the biomass N (Voroney et al., 1993).

Soil samples were obtained at various times throughout each growing season and at three depths as explained in section 2.4.3. These samples were analysed for mineral  $\text{NO}_3^-$  - N and  $\text{NH}_4^+$  - N. In addition, some of the samples were analysed for total soluble nitrogen (TSN) and total organic carbon (TOC).  $\text{CHCl}_3$ -extractable N and C were calculated from these various measurements as explained in section 2.4.4. Table 6.1 summarizes the sampling dates and the measured parameters for each sampling date and the measured values are given as ASCII files on the accompanying diskette. The names of these files and a description of their contents are given in Appendix 8. The data will be discussed separately for each year with ANOVAs being performed for the appropriate measured parameters at the various sampling dates.

A general discussion of the 1991 and 1992 data will be followed by a more detailed discussion of the 1993 data. The 1993 data are discussed in more detail since denitrification measurements (Chapter 7) and detailed solution sampler measurements (Chapter 5) were also made in 1993.

## 6.2 1991 Results

Tables 6.2 through 6.5 give the summary of F values for the ANOVAs of mineral  $\text{NO}_3^-$ , mineral  $\text{NH}_4^+$ ,  $\text{CHCl}_3$ -extractable N and C for the various treatment effects as measured in 1991, respectively. Note that the plots which received N applications in the fall were not implemented until the December 9, 1991 measurements. These various N application F values for those dates prior to December 9, 1991 are denoted with a hyphen (-) (Tables 6.2 through 6.5).



Table 6.1: Summary of sampling dates and measured parameters for 1991, 1992 and 1993 growing seasons.

Year	Sampling Date	Measured Parameter		
		Mineral N	CHCl <sub>3</sub> -Extractable N	CHCl <sub>3</sub> -Extractable C
1991	May 13	Yes	Yes	Yes
	June 12	Yes	Yes	Yes
	July 8	Yes	Yes	Yes
	December 9	Yes	No	No
1992	May 6	Yes	No	No
	May 26	Yes	Yes	Yes
	June 23	Yes	No	No
1993	May 3	Yes	No	No
	May 17	Yes	No	No
	June 1	Yes	No	No
	June 14	Yes	No	No
	July 6	Yes	Yes	Yes
	October 27	Yes	No	No

#### 6.2.1 Ammonium Results

Figures 6.1 through 6.4 give plots of the  $\text{NH}_4^+$  ( $\text{kg N ha}^{-1}$ ) for the various N sources as measured at the three depths and for the total in the 0 - 60 cm depth. The mean of the control plots is represented with the letter C in the legend of the figures. There was a significant N source, N rate and N source with N rate interaction on the first sampling date (May 13, 1991) (Table 6.2). These differences were due to the fact that the soil sampling occurred after the  $\text{NH}_4\text{NO}_3$  source was applied but before the LCM or SBM sources were applied (Table 4.1). These differences are obvious in Figures 6.1 through 6.4, however, it is unclear why differences were observed at the lower depths. Contamination of the lower samples with the surface applied  $\text{NH}_4\text{NO}_3$  may have been the reason for these differences.  $\text{NH}_4^+$  values remained small over the growing season for all sources and no differences were observed at the later dates until the December 9 applications (Table 6.2). Although much of the mineral N in the LCM source is in the  $\text{NH}_4^+$  form (Table 2.4), it is reasonable that plant uptake and nitrification would have minimized the amounts of  $\text{NH}_4^+$ .

Table 6.2: Summary of F values for the various treatments for the 1991  $\text{NH}_4^+$  measurements.

Source of Variation	Sampling Date											
	May 13			June 12			July 8			December 9		
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	25.4 <sup>***</sup>	17.6 <sup>***</sup>	8.3 <sup>***</sup>	2.4 <sup>*</sup>	NS	NS	NS	NS	3.1 <sup>*</sup>	3.64 <sup>**</sup>	2.6 <sup>*</sup>	NS
N Rate	5.9 <sup>***</sup>	5.1 <sup>***</sup>	3.5 <sup>**</sup>	NS	NS	NS	NS	NS	NS	3.61 <sup>**</sup>	NS	NS
N Application Time	-	-	-	-	-	-	-	-	-	NS	NS	NS
Source * Rate * Time	-	-	-	-	-	-	-	-	-	2.39 <sup>*</sup>	3.3 <sup>**</sup>	NS
Source * Rate	6.3 <sup>***</sup>	5.7 <sup>***</sup>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Source * Time	-	-	-	-	-	-	-	-	-	NS	NS	NS
Rate * Time	-	-	-	-	-	-	-	-	-	4.2 <sup>**</sup>	NS	NS

<sup>+</sup> Sampling depths (cm)

\* \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Table 6.3: Summary of F values for the various treatments for the 1991 NO<sub>3</sub> measurements.

Source of Variation	Sampling Date											
	May 13			June 12			July 8			December 9		
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	116 ***	37.3 ***	15.6 ***	102 ***	9.1 ***	NS	56.1 ***	8.6 ***	6.4 ***	23.4 ***	32.6 ***	30.3 ***
N Rate	15.4 ***	2.5 *	3.5 ***	26.6 ***	8.6 ***	2.9 *	9.4 ***	NS	NS	8.5 ***	15.7 ***	6.9 **
N Application Time	-	-	-	-	-	-	-	-	-	62.3 ***	65.3 ***	53.4 ***
Source * Rate * Time	-	-	-	-	-	-	-	-	-	4.9 ***	NS	NS
Source * Rate	12.8 ***	4.6 ***	4.9 ***	9.8 ***	20.9 ***	NS	3.2 **	NS	NS	4.5 ***	4.6 **	3.8 **
Source * Time	-	-	-	-	-	-	-	-	-	19.6 ***	7.4 ***	3.2 **
Rate * Time	-	-	-	-	-	-	-	-	-	3.1 *	2.4 *	NS

<sup>+</sup> Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Table 6.5: Summary of F values for the various treatments for the 1991  $\text{CHCl}_3$ -extractable C measurements.

Source of Variation	Sampling Date											
	May 13			June 12			July 8			December 9		
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	NS	6.5 <sup>***</sup>	6.2 <sup>***</sup>	5.0 <sup>***</sup>	NS	3.5 <sup>**</sup>	2.7 <sup>*</sup>	NS	NS	ND	ND	ND
N Rate	NS	NS	NS	3.1 <sup>*</sup>	NS	NS	NS	NS	NS	ND	ND	ND
N Application Time	-	-	-	-	-	-	-	-	-	ND	ND	ND
Source * Rate * Time	-	-	-	-	-	-	-	-	-	ND	ND	ND
Source * Rate	NS	NS	NS	NS	NS	NS	NS	NS	NS	ND	ND	ND
Source * Time	-	-	-	-	-	-	-	-	-	ND	ND	ND
Rate * Time	-	-	-	-	-	-	-	-	-	ND	ND	ND

<sup>+</sup> Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Figure 6.1:  $\text{NH}_4^+$  as a function of N source from the 0-15 cm depth.

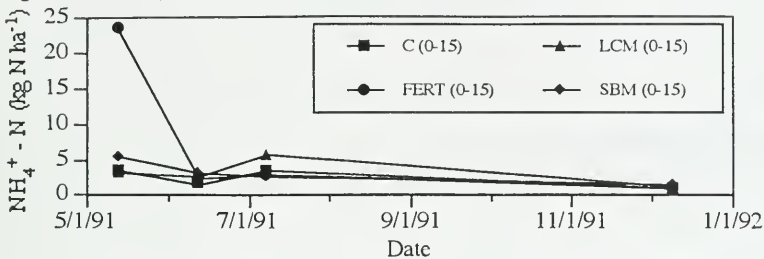


Figure 6.2:  $\text{NH}_4^+$  as a function of N source from the 15-30 cm depth.

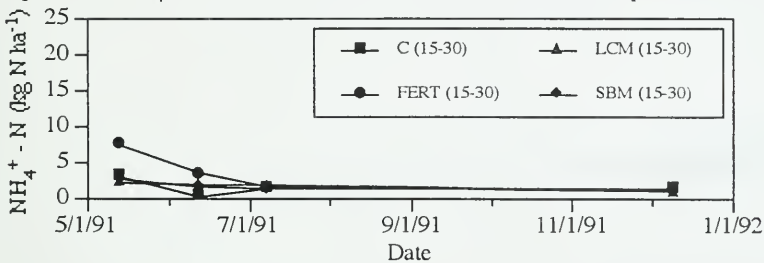


Figure 6.3:  $\text{NH}_4^+$  as a function of N source from the 30-60 cm depth.

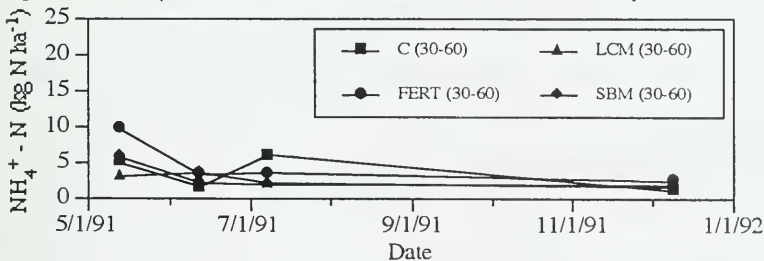


Figure 6.4:  $\text{NH}_4^+$  as a function of N source from the 0-60 cm depth.

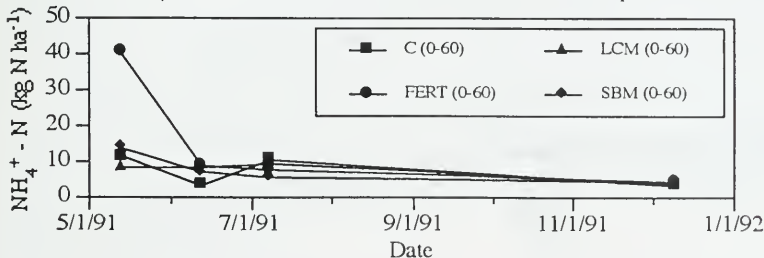


Figure 6.5:  $\text{NH}_4^+$  as a function of N rate from the 0-15 cm depth.

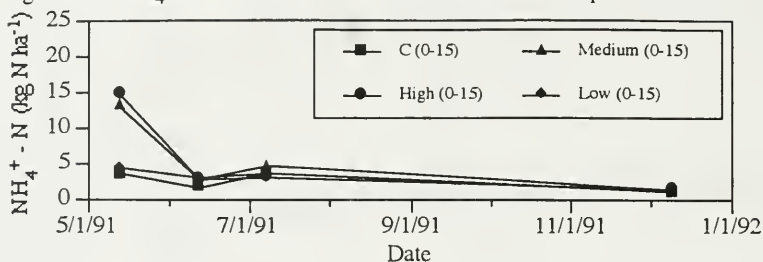


Figure 6.6:  $\text{NH}_4^+$  as a function of N rate from the 15-30 cm depth.

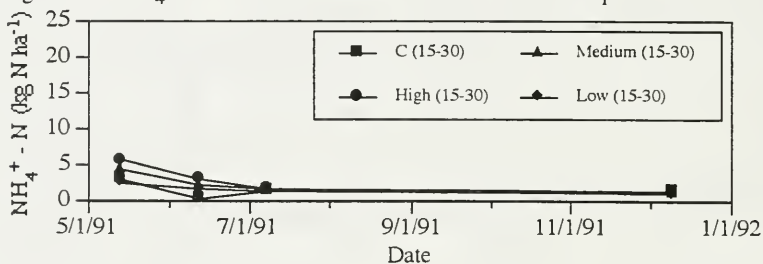


Figure 6.7:  $\text{NH}_4^+$  as a function of N rate from the 30-60 cm depth.

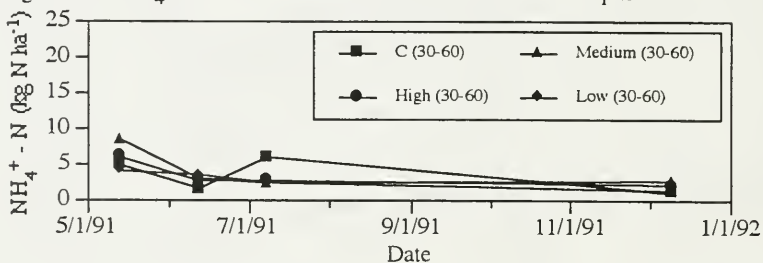
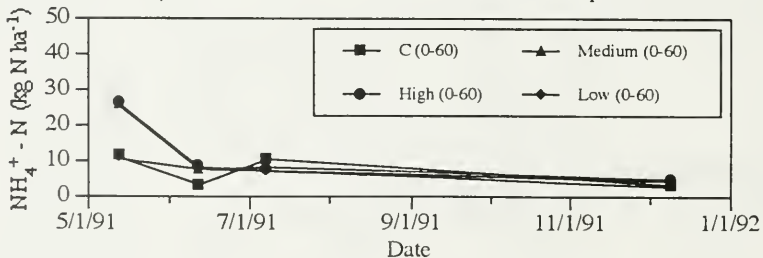


Figure 6.8:  $\text{NH}_4^+$  as a function of N rate from the 0-60 cm depth.



Figures 6.5 through 6.8 give the measured amounts of  $\text{NH}_4^+$  for the various N rates at the three depths and for the total  $\text{NH}_4^+$  in the 0 - 60 cm depth. Significant differences were observed on the first sampling date at the three depths (Table 6.2). Again, it appears as though sample contamination may have caused these differences at the lower depths. Also, the small or negligible difference between treated plots and the control plots suggests that nitrification of  $\text{NH}_4^+$  was occurring rapidly at this site. In addition, the low measured amounts of mineral  $\text{NH}_4^+$  at the various depths at this site was consistent with the low concentrations of  $\text{NH}_4^+$  measured with the solution samplers (Chapter 5).

### 6.2.2 Nitrate Results

Table 6.3 indicated similar but more significant differences, with respect to  $\text{NO}_3^-$  levels, as were observed with  $\text{NH}_4^+$  (Table 6.2). This was consistent with the hypothesis that nitrification was occurring at this site. Again, the first sampling date indicated that the LCM and SBM sources were approximately equal but less than the  $\text{NH}_4\text{NO}_3$  source which was attributed to the fact that the sampling was done after the  $\text{NH}_4\text{NO}_3$  application but prior to the LCM and SBM applications. At subsequent sampling dates, there is a consistent trend, at all depths, of  $\text{NO}_3^-$  levels in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$  (Figures 6.9 through 6.12). This is consistent with the amounts of available  $\text{NO}_3^-$  that was in each source after nitrification is taken into account (Table 2.4) and it was also consistent with the observed trends in the solution sampler data (Chapter 5). In addition, the  $\text{NO}_3^-$  in all N sources was observed to decrease from the June 12 sampling date to the July 8 sampling date. This was attributed to plant uptake and immobilization of  $\text{NO}_3^-$ . The low amounts of available  $\text{NO}_3^-$  in the SBM treatments was also consistent with the reduced grain yield observed in the SBM plots in 1991 (Table 4.3). Also of interest is the increase in  $\text{NO}_3^-$  from the July 8 sampling date to the December 9 sampling date at the two lower depths but not at the 0 - 15 cm depth. This was attributed to the  $\text{NO}_3^-$  in the 0 - 15 cm depth being leached down to the lower depths over the fall of 1991.

Figure 6.9:  $\text{NO}_3^-$  as a function of N source from the 0-15 cm depth.

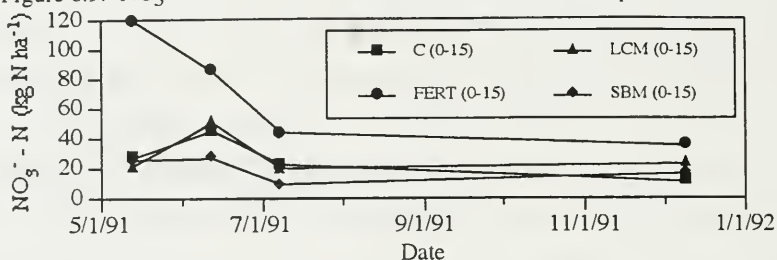


Figure 6.10:  $\text{NO}_3^-$  as a function of N source from the 15-30 cm depth.

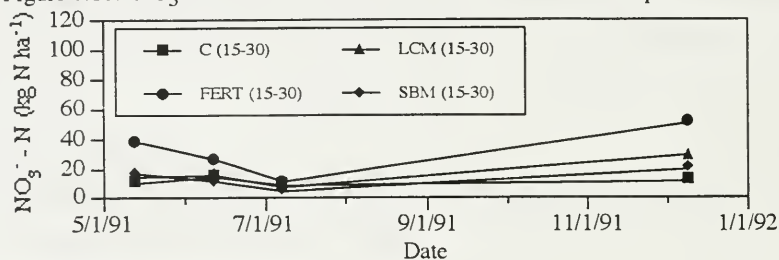


Figure 6.11:  $\text{NO}_3^-$  as a function of N source from the 30-60 cm depth.

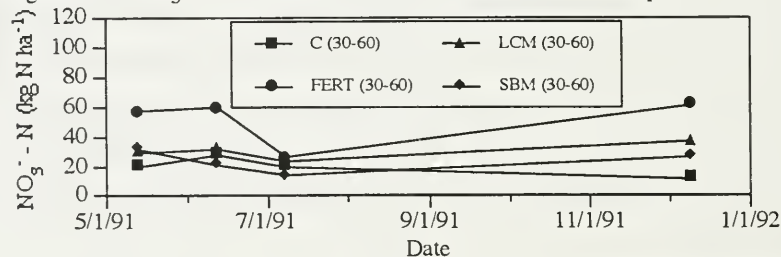


Figure 6.12:  $\text{NO}_3^-$  as a function of N source from the 0-60 cm depth.

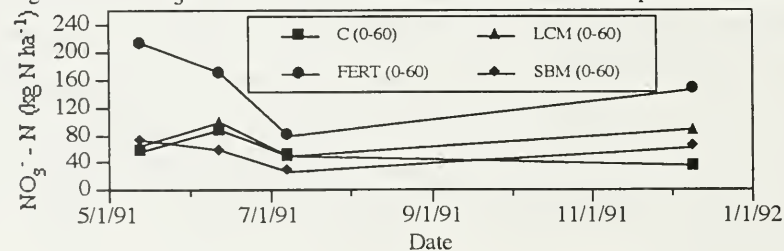




Figure 6.13:  $\text{NO}_3^-$  as a function of N rate from the 0-15 cm depth.

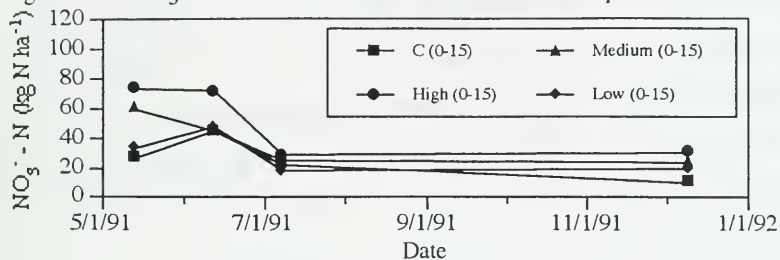


Figure 6.14:  $\text{NO}_3^-$  as a function of N rate from the 15-30 cm depth.

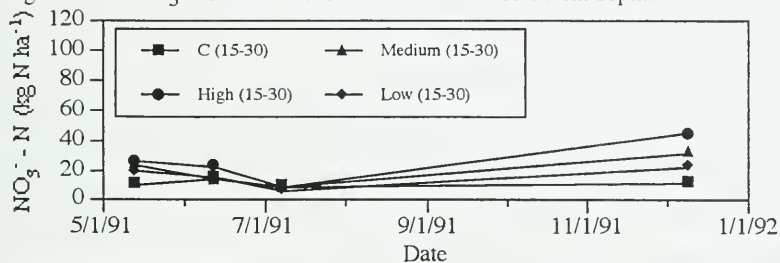


Figure 6.15:  $\text{NO}_3^-$  as a function of N rate from the 30-60 cm depth.

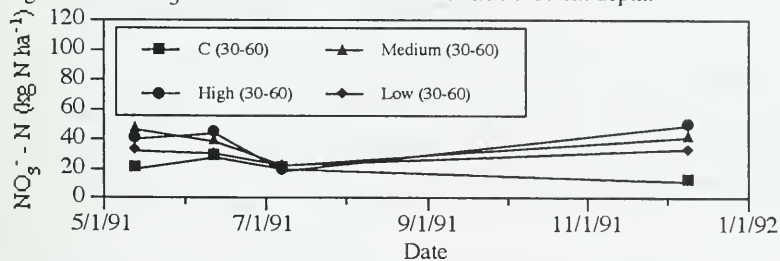
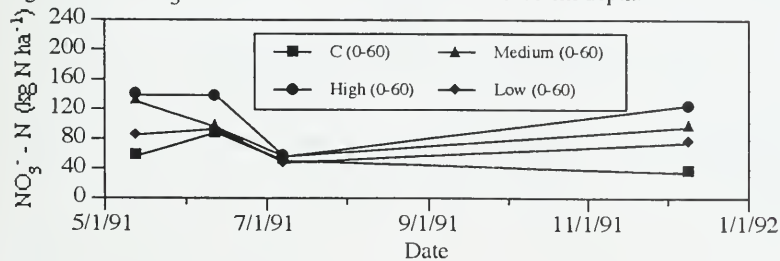


Figure 6.16:  $\text{NO}_3^-$  as a function of N rate from the 0-60 cm depth.



Averaged over N source, the N rate amounts of  $\text{NO}_3^-$  are given for the various depths in Figures 6.13 through 6.16. There was a consistent significant trend of High > Medium > Low for the 0 - 15 cm depth for all dates (Table 6.3). All three rates had greater amounts of  $\text{NO}_3^-$  than the control plots at each depth by the December 9, 1991 sampling date (Figures 6.13 through 6.16). Again, the decrease in amounts of  $\text{NO}_3^-$  from the June 12 to July 8 dates was attributed to denitrification and plant uptake.

### 6.2.3 $\text{CHCl}_3$ -extractable N Results

There were negligible significant differences observed in the 1991  $\text{CHCl}_3$ -extractable N measurements (Table 6.4). Figures 6.17 through 6.24 give the N source and N application rate plots of  $\text{CHCl}_3$ -extractable N over the growing season. Differences may have been minor because of the lack of time required for the growth of the microbial biomass in response to treatment.  $\text{CHCl}_3$ -extractable N values decreased with depth but remained relatively uniform throughout the 1991 growing season. In addition, there was little difference between the treated plots and the control plots.

$\text{CHCl}_3$ -extractable N values also indicated little change throughout the 1991 growing season when averaged over N source (Figures 6.21 through 6.24). There was no consistent difference between N rates. In addition, there was little difference between treated plots and the control plots.

Figure 6.17:  $\text{CHCl}_3$ -extractable N for the various N sources from the 0 - 15 cm depth.

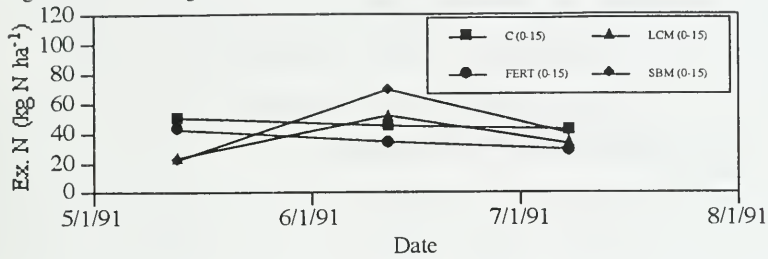


Figure 6.18:  $\text{CHCl}_3$ -extractable N for the various N sources from the 15 - 30 cm depth.

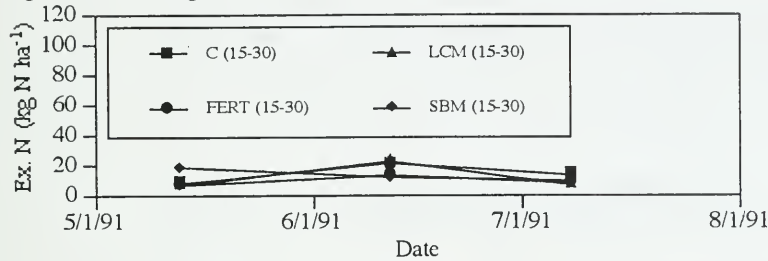


Figure 6.19:  $\text{CHCl}_3$ -extractable N for the various N sources from the 30 - 60 cm depth.

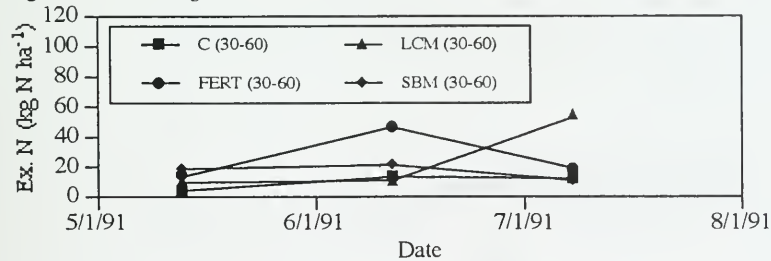


Figure 6.20:  $\text{CHCl}_3$ -extractable N for the various N sources from the 0 - 60 cm depth.

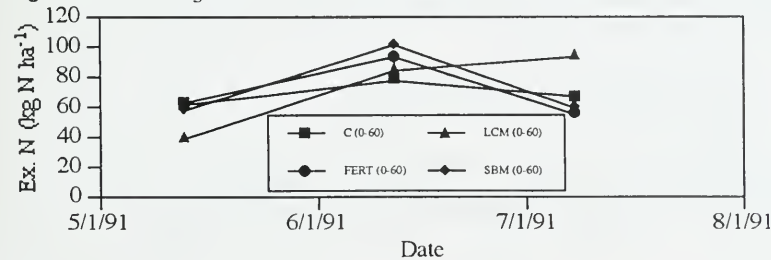


Figure 6.21:  $\text{CHCl}_3$ -extractable N for the various N rates at the 0 - 15 cm depth.

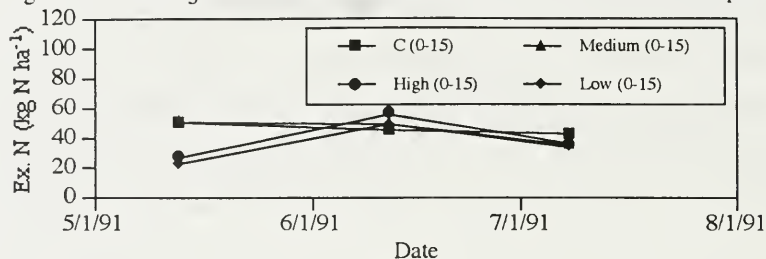


Figure 6.22:  $\text{CHCl}_3$ -extractable N for the various N rates at the 15 - 30 cm depth.

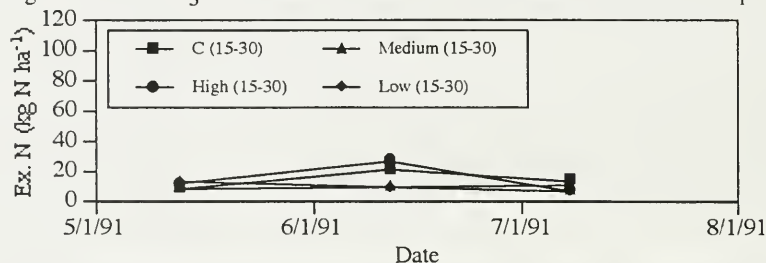


Figure 6.23:  $\text{CHCl}_3$ -extractable N for the various N rates at the 30 - 60 cm depth.

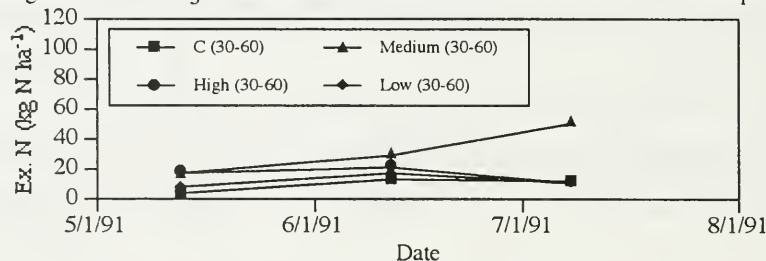
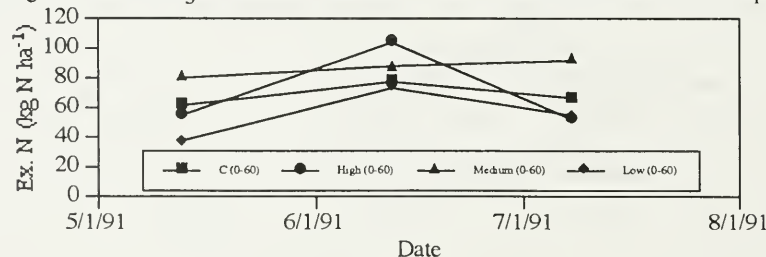


Figure 6.24:  $\text{CHCl}_3$ -extractable N for the various N rates from the 0 - 60 cm depth.



#### 6.2.4 CHCl<sub>3</sub>-extractable C

Observed trends in CHCl<sub>3</sub>-extractable C measurements were similar to those of the CHCl<sub>3</sub>-extractable N values (Figures 6.25 through 6.32). Measured CHCl<sub>3</sub>-extractable C amounts were larger in the 0 - 15 cm depth than the other two depths. This was attributed to the fact that microbial biomass is greatest near the soil surface and also this is the depth into which the N sources were mixed. It is unclear why the largest differences were observed on the first sampling date when only the NH<sub>4</sub>NO<sub>3</sub> source had been applied. The CHCl<sub>3</sub>-extractable C for the SBM source, from the 0 - 15 cm depth, appeared to be somewhat larger than the other sources by the July 8 sampling date. Negligible differences between N rates were observed with respect to CHCl<sub>3</sub>-extractable C values (Figures 6.29 through 6.32).

Figure 6.25:  $\text{CHCl}_3$ -extractable C for the various N sources from the 0 - 15 cm depth.

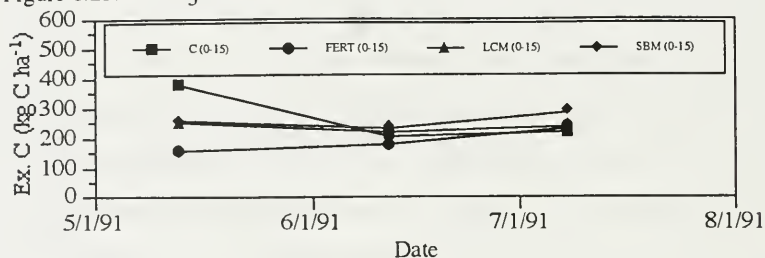


Figure 6.26:  $\text{CHCl}_3$ -extractable C for the various N sources from the 15 - 30 cm depth.

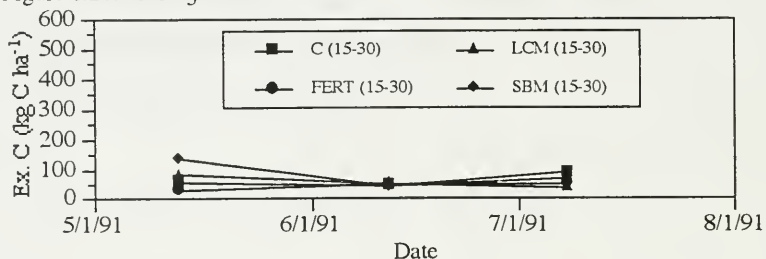


Figure 6.27:  $\text{CHCl}_3$ -extractable C for the various N sources from the 30 - 60 cm depth.

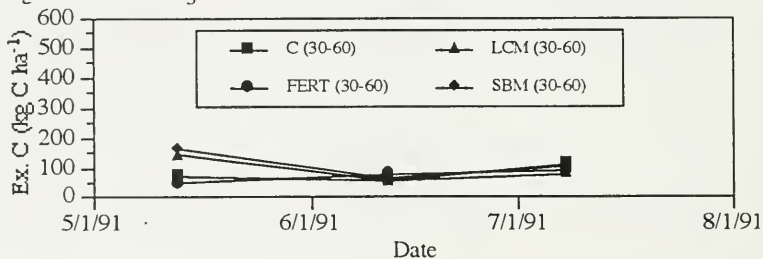


Figure 6.28:  $\text{CHCl}_3$ -extractable C for the various N sources from the 0 - 60 cm depth.

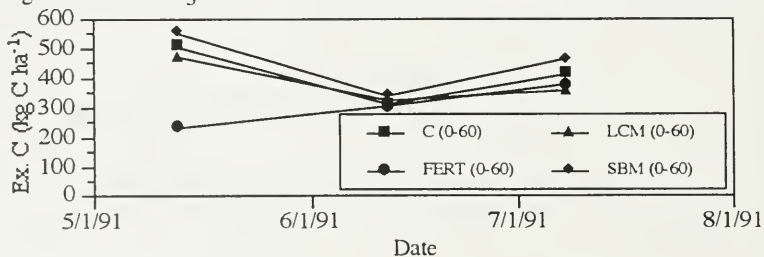


Figure 6.29:  $\text{CHCl}_3$ -extractable C for the various N rates at the 0 - 15 cm depth.

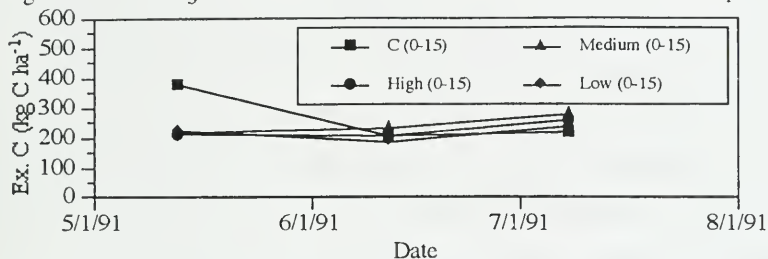


Figure 6.30:  $\text{CHCl}_3$ -extractable C for the various N rates at the 15 - 30 cm depth.

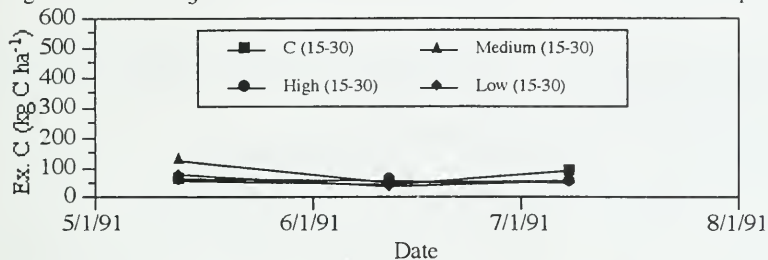


Figure 6.31:  $\text{CHCl}_3$ -extractable C for the various N rates at the 30 - 60 cm depth.

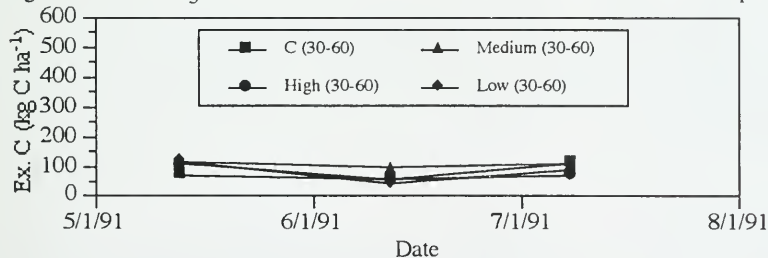
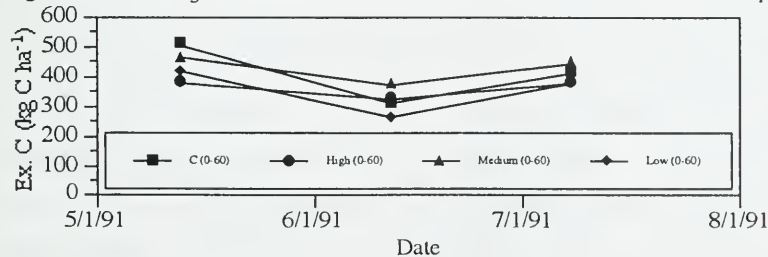


Figure 6.32:  $\text{CHCl}_3$ -extractable C for the various N rates from the 0 - 60 cm depth.



### 6.3 1992 Results

The plots were sampled once for  $\text{CHCl}_3$ -extractable C and extractable N and three times for mineral  $\text{NO}_3^-$  and  $\text{NH}_4^+$ , respectively in 1992 (Table 6.1). In addition, the extractable N and  $\text{CHCl}_3$ -extractable C measurements were only made on the plots which received medium rates of N. As a result, only the mineral N measurements will be discussed in this section. However, the 1992  $\text{CHCl}_3$ -extractable C and extractable N ANOVA F values are given in Table 6.6. The actual measurements will be presented in section 6.4 in conjunction with the other two years' measurements.

Table 6.6: Summary of F values for the various treatments for the 1992 extractable N and  $\text{CHCl}_3$ -extractable C measurements made on May 26, 1992.

Source of Variation	Extractable N			$\text{CHCl}_3$ -extractable C		
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	NS	4.4 <sup>**</sup>	7.6 <sup>***</sup>	23.2 <sup>***</sup>	7.7 <sup>***</sup>	10.3 <sup>***</sup>
N Application Time	NS	NS	NS	8.9 <sup>***</sup>	NS	NS
N Appl. Time * Source	NS	NS	6.1 <sup>***</sup>	5.9 <sup>***</sup>	4.8 <sup>**</sup>	6.4 <sup>***</sup>

<sup>+</sup> Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

#### 6.3.1 Ammonium Results

Table 6.7 gives the ANOVA F values for the 1992  $\text{NH}_4^+$  measurements and Figures 6.33 through 6.44 give the temporal changes in these measurements averaged over various treatments. Amounts of  $\text{NH}_4^+$  remained low as was observed in 1991. This was consistent with low concentrations of  $\text{NH}_4^+$  measured with the solution samplers. Also, it was consistent with the idea that nitrification occurs quite rapidly at this site. The total amount of  $\text{NH}_4^+$  in the 0 - 60 cm depth indicated that all of the N sources produced amounts greater than the control plots. However, this was only the case at the June 23 sampling date (Figure 6.36). Prior to N source application (May 13 - May 15, 1992) there was no difference between N sources. The LCM source was significantly



Table 6.7: Summary of F values for the various treatments for the 1992  $\text{NH}_4^+$  measurements.

Source of Variation	Sampling Date											
	May 6						May 26					
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	NS	NS	5.5 <sup>***</sup>	NS	NS	3.6 <sup>**</sup>	4.4 <sup>**</sup>	NS	NS	NS	NS	NS
N Rate	NS	NS	5.9 <sup>***</sup>	4.0 <sup>**</sup>	5.9 <sup>***</sup>	4.9 <sup>**</sup>	NS	NS	NS	NS	NS	NS
N Application Time	NS	NS	3.5 <sup>*</sup>	NS	NS	5.4 <sup>**</sup>	NS	NS	NS	NS	NS	NS
Source * Rate * Time	NS	NS	NS	5.2 <sup>***</sup>	NS	NS	NS	NS	NS	NS	NS	NS
Source * Rate	NS	NS	NS	NS	NS	3.6 <sup>**</sup>	NS	NS	NS	NS	NS	NS
Source * Time	NS	NS	NS	5.6 <sup>***</sup>	NS	NS	NS	NS	NS	NS	NS	NS
Rate * Time	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

<sup>+</sup> Sampling depths (cm)

\* \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

N/D - measurement not done

larger than the other two sources only at the lower depth (Table 6.7, Figures 6.35, 6.36). This was consistent with LCM containing the most  $\text{NH}_4^+$  - N at the time of application. Again, amounts of  $\text{NH}_4^+$  decreased with depth in all treatments.

There was little difference between N application rates in terms of soil  $\text{NH}_4^+$ . However, there was an indication that the high and medium rate treated plots remained greater than the low rate treated plots (Figures 6.37 through 6.40). These differences became more apparent at the June 23, 1992 sampling date. Negligible differences between spring and fall treated plots were observed (Table 6.7, Figures 6.41 through 6.44). Again, the low measured values of  $\text{NH}_4^+$  at this site suggested that  $\text{NO}_3^-$  is the prominent form of N available to plants as well as leaching.

### 6.3.2 Nitrate Results

Significant differences were more evident between the various treatments with respect to amounts of soil  $\text{NO}_3^-$  (Table 6.8). However, there were negligible differences between N sources on the first sampling date (Figures 6.45 through 6.46) from the 0 - 15 cm depth. This was consistent with the  $\text{Cl}^-$  leaching experiments which indicated that much of the  $\text{NO}_3^-$  remaining from the previous year's applications would have been leached downwards over the winter. This was also indicated by the increased difference between sources at the lower depths in the soil profile. Differences between N sources increased after the spring 1992 applications and all treated plots had greater soil  $\text{NO}_3^-$  amounts than the control plots. Also, there was a consistent trend of decreasing amounts of soil  $\text{NO}_3^-$  in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . Again, this was consistent with measurements of the soil solution concentrations of  $\text{NO}_3^-$  - N (Chapter 5). It is of interest to note that amounts of  $\text{NO}_3^-$  remained relatively uniform over the two sampling dates (May 26, 1992 to June 23, 1992) when plant uptake of N would have been expected to lower the measured amounts. However, the plants were only at about the 6 leaf stage (Table 4.5) by mid June which was most likely just prior to the period of greatest N uptake.

Table 6.8: Summary of F values for the various treatments for the 1992  $\text{NO}_3^-$  measurements.

Source of Variation	Sampling Date											
	May 6				May 26				June 23			
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	NS	10.3 <sup>***</sup>	37.8 <sup>***</sup>	11.4 <sup>***</sup>	9.6 <sup>***</sup>	76.4 <sup>***</sup>	31.6 <sup>***</sup>	6.1 <sup>***</sup>	30.0 <sup>***</sup>			
N Rate	4.3 <sup>**</sup>	7.1 <sup>***</sup>	20.4 <sup>***</sup>	12.2 <sup>***</sup>	87.5 <sup>***</sup>	14.5 <sup>***</sup>	9.2 <sup>***</sup>	2.6 <sup>*</sup>	7.5 <sup>***</sup>			
N Application Time	NS	41.6 <sup>***</sup>	124 <sup>***</sup>	157 <sup>***</sup>	12.1 <sup>***</sup>	NS	105 <sup>***</sup>	24.4 <sup>***</sup>	NS			
Source * Rate * Time	2.2 <sup>*</sup>	NS	3.3 <sup>**</sup>	NS	NS	3.9 <sup>***</sup>	4.1 <sup>***</sup>	2.9 <sup>***</sup>	3.1 <sup>*</sup>			
Source * Rate	NS	2.5 <sup>*</sup>	8.8 <sup>***</sup>	2.2 <sup>*</sup>	NS	6.8 <sup>***</sup>	3.4 <sup>**</sup>	NS	5.5 <sup>***</sup>			
Source * Time	NS	2.5 <sup>*</sup>	9.1 <sup>***</sup>	4.6 <sup>**</sup>	3.3 <sup>**</sup>	17.6 <sup>***</sup>	17.9 <sup>***</sup>	NS	NS			
Rate * Time	NS	4.0 <sup>**</sup>	4.4 <sup>**</sup>	8.2 <sup>***</sup>	2.7 <sup>*</sup>	NS	12.1 <sup>***</sup>	2.8 <sup>*</sup>	3.8 <sup>**</sup>			

<sup>+</sup> Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Figure 6.33:  $\text{NH}_4^+$  as a function of N source from the 0-15 cm depth in 1992.

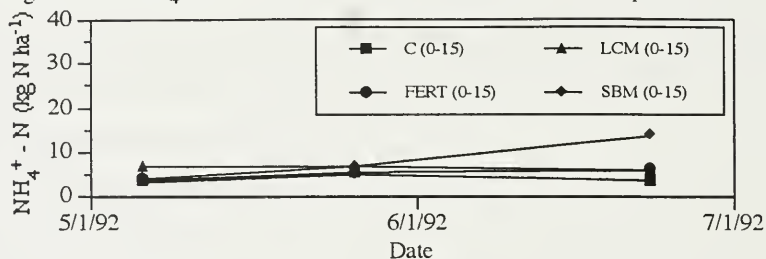


Figure 6.34:  $\text{NH}_4^+$  as a function of N source from the 15-30 cm depth in 1992.

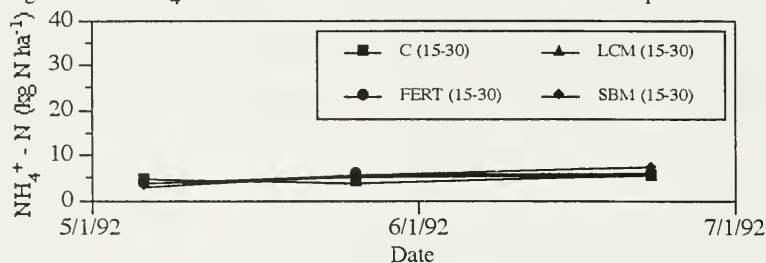


Figure 6.35:  $\text{NH}_4^+$  as a function of N source from the 30-60 cm depth in 1992.

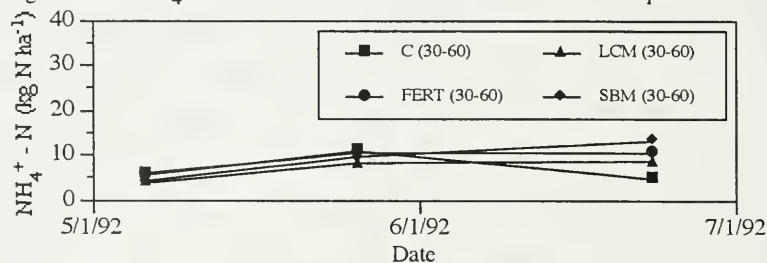


Figure 6.36:  $\text{NH}_4^+$  as a function of N source from the 0-60 cm depth in 1992.

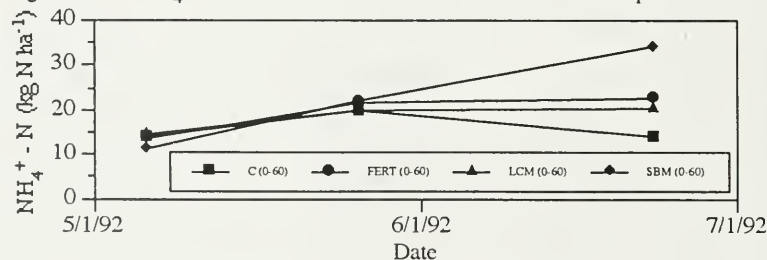


Figure 6.37:  $\text{NH}_4^+$  as a function of N rate from the 0-15 cm depth in 1992.

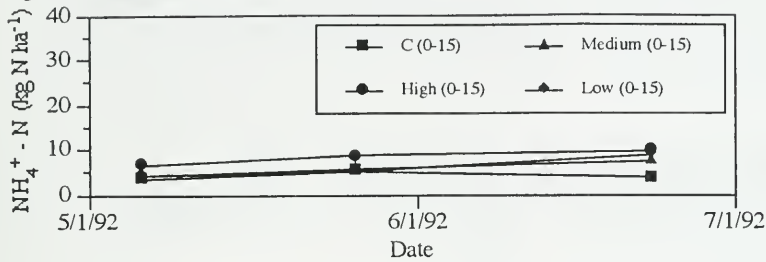


Figure 6.38:  $\text{NH}_4^+$  as a function of N rate from the 15-30 cm depth in 1992.

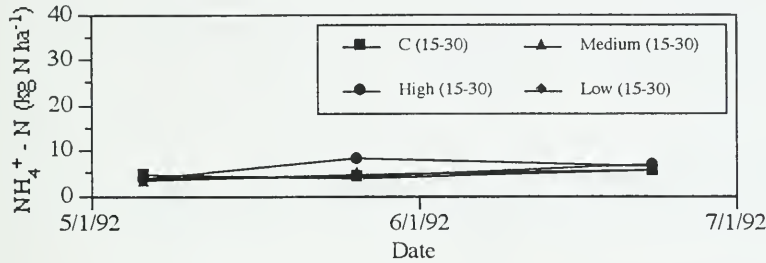


Figure 6.39:  $\text{NH}_4^+$  as a function of N rate from the 30-60 cm depth in 1992.

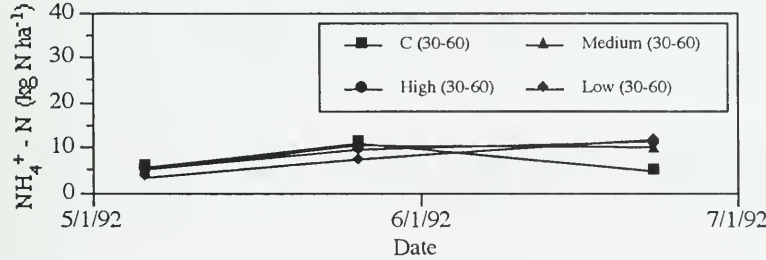


Figure 6.40:  $\text{NH}_4^+$  as a function of N rate from the 0-60 cm depth in 1992.

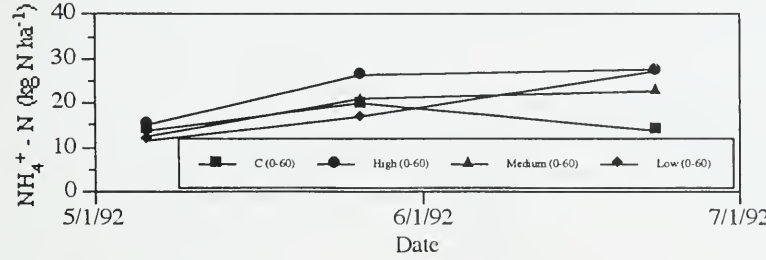


Figure 6.41:  $\text{NH}_4^+$  as a function of N application time from the 0-15 cm depth in 1992.

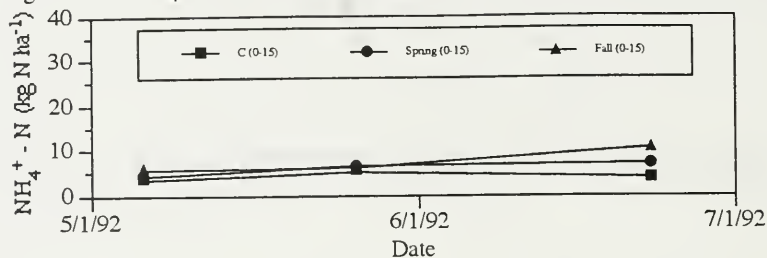


Figure 6.42:  $\text{NH}_4^+$  as a function of N application time from the 15-30 cm depth in 1992.

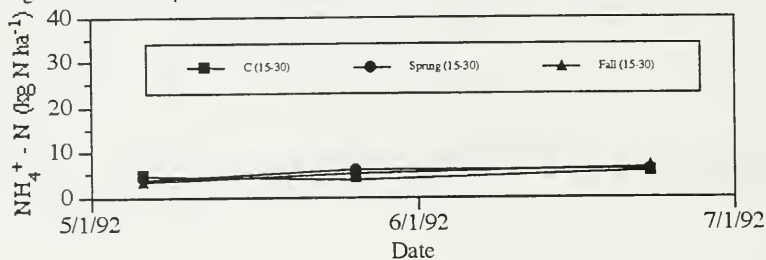


Figure 6.43:  $\text{NH}_4^+$  as a function of N application time from the 30-60 cm depth in 1992.

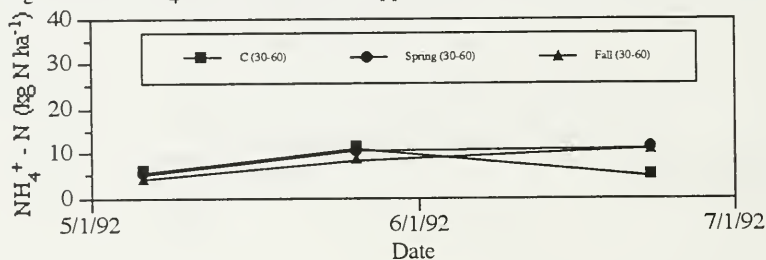


Figure 6.44:  $\text{NH}_4^+$  as a function of N application time from the 0-60 cm depth in 1992.

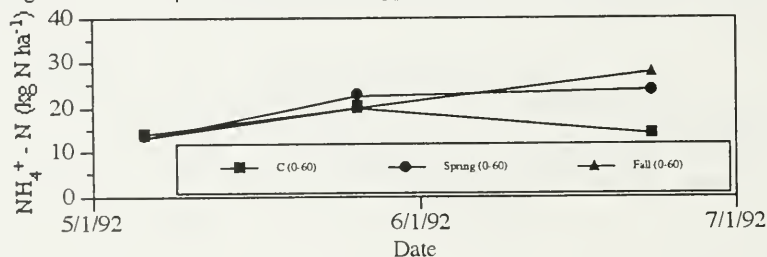


Figure 6.45:  $\text{NO}_3^-$  as a function of N source from the 0-15 cm depth in 1992.

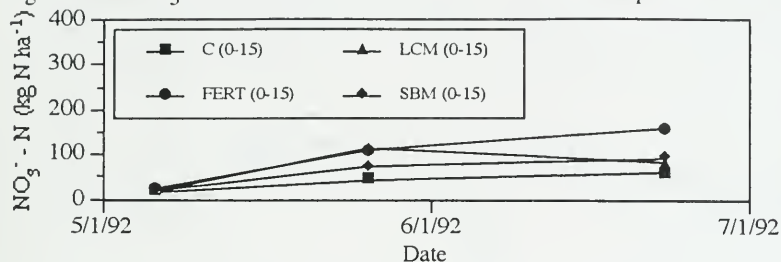


Figure 6.46:  $\text{NO}_3^-$  as a function of N source from the 15-30 cm depth in 1992.

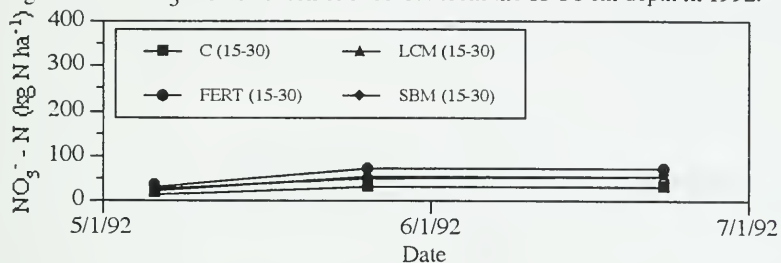


Figure 6.47:  $\text{NO}_3^-$  as a function of N source from the 30-60 cm depth in 1992.

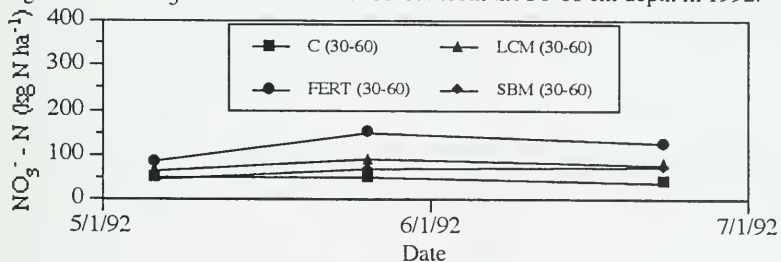


Figure 6.48:  $\text{NO}_3^-$  as a function of N source from the 0-60 cm depth in 1992.

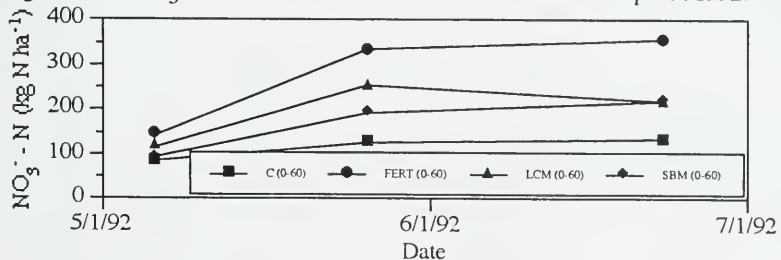


Figure 6.49:  $\text{NO}_3^-$  as a function of N rate from the 0-15 cm depth in 1992.

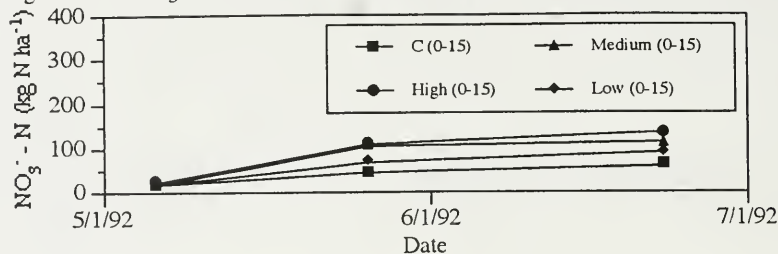


Figure 6.50:  $\text{NO}_3^-$  as a function of N rate from the 15-30 cm depth in 1992.

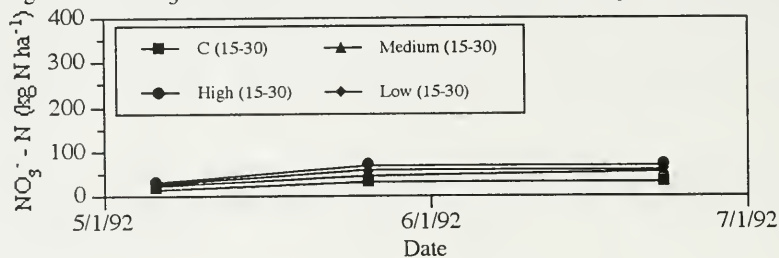


Figure 6.51:  $\text{NO}_3^-$  as a function of N rate from the 30-60 cm depth in 1992.

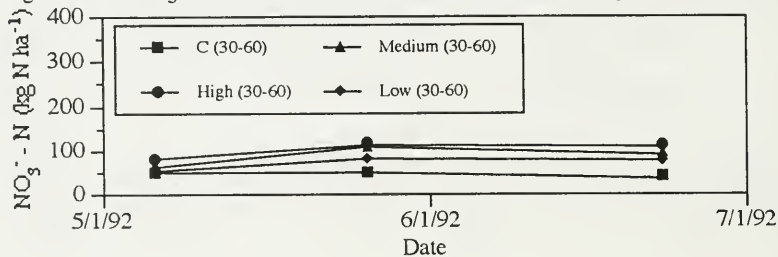


Figure 6.52:  $\text{NO}_3^-$  as a function of N rate from the 0-60 cm depth in 1992.

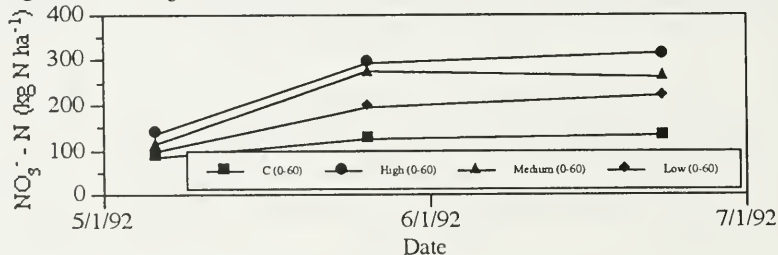




Figure 6.53:  $\text{NO}_3^-$  as a function of N application time from the 0-15 cm depth in 1992.

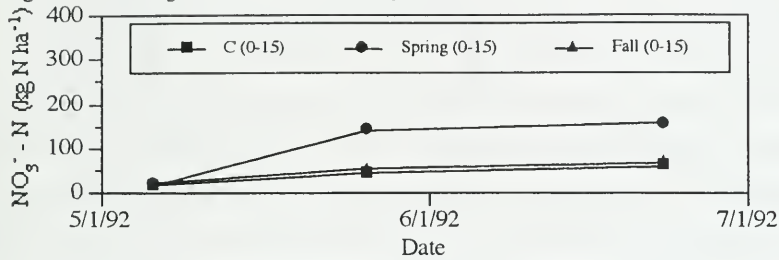


Figure 6.54:  $\text{NO}_3^-$  as a function of N application time from the 15-30 cm depth in 1992.

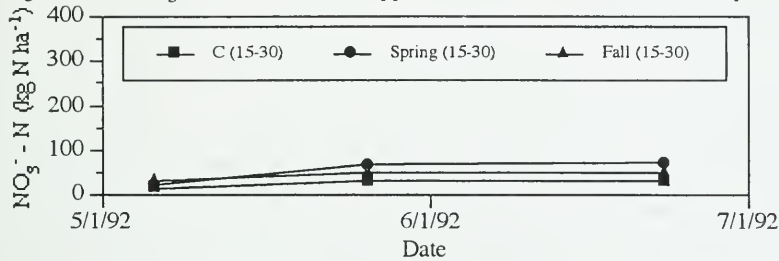


Figure 6.55:  $\text{NO}_3^-$  as a function of N application time from the 30-60 cm depth in 1992.

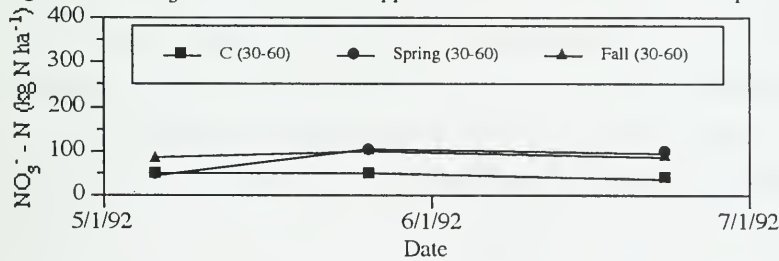
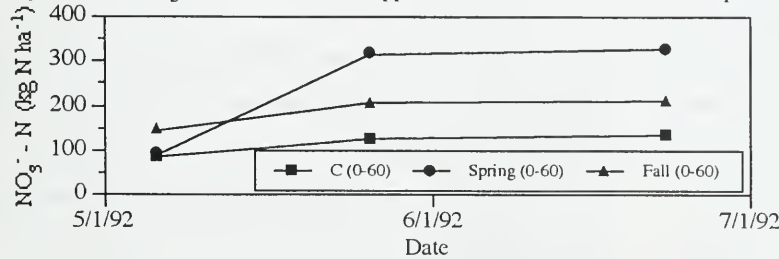


Figure 6.56:  $\text{NO}_3^-$  as a function of N application time from the 0-60 cm depth in 1992.



Soil  $\text{NO}_3^-$  amounts, as a function of N application rate, indicated similar differences to the N source values (Figures 6.49 through 6.52). Over the 0 - 60 cm depth, there was a consistent trend of decreasing soil  $\text{NO}_3^-$  amounts in the order of High > Medium > Low > Control (Figure 6.52). The effect of N application time was obvious with the  $\text{NO}_3^-$  values (Figures 6.53 through 6.56). The differences were largest in the 0 - 15 cm depth where the manures and fertilizer were incorporated. Differences were negligible at the two lower depths due to a lack of percolating water at this time of year. The large net drainage measured in the summer and fall of 1992 did not commence until mid July (Chapter 5).

## 6.4 1993 Results

Soil  $\text{NO}_3^-$  and  $\text{NH}_4^+$  measurements were made six times throughout the 1993 growing season (Table 6.1). Measurements of  $\text{CHCl}_3$ -extractable N and C were made once in 1993 (Table 6.1). The  $\text{NO}_3^-$  and  $\text{NH}_4^+$  measurements will be presented in a fashion similar to the solution sampler data which will allow interpretation of the interaction terms given in the ANOVA tables (Tables 6.9 and 6.10). The  $\text{CHCl}_3$ -extractable N and C data will be presented in conjunction with the 1991 and 1992 measurements so that any temporal trends may be discussed. N sources were applied between May 10 and May 12, 1993 and the corn was planted on May 13, 1993. A prolonged cold period after planting delayed emergence until June 7, 1993 and the crop had reached the 10 leaf stage by July 24, 1993 (Table 4.11).

### 6.4.1 Ammonium Results

The ANOVA F values for the soil  $\text{NH}_4^+$  measurements for the various treatments are given in Table 6.9. Since amounts of soil  $\text{NH}_4^+$  remained low and comparable to the other two years of measurements, figures are given for the total amount of soil  $\text{NH}_4^+$  in the 0 - 60 cm depth only (Figures 6.57 through 6.68). The largest differences in soil  $\text{NH}_4^+$  measurements were observed at the high rates of application in the spring (Figure 6.57).

Table 6.9: Summary of F values for the various treatments for the 1993  $\text{NH}_4^+$  measurements.

Source of Variation	Sampling Date											
	May 3			May 17			June 1			June 14		
	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60
N Source	5.3	***	2.6	3.1	***	5.7	***	NS	NS	6.8	***	2.6
N Rate	NS	5.2	***	5.4	***	7.2	***	6.0	***	3.9	***	4.6
N Application Time	6.1	***	NS	14.5	***	NS	5.7	***	8.4	***	NS	7.7
Source * Rate * Time	NS	NS	NS	3.6	***	NS	2.9	***	NS	NS	NS	NS
Source * Rate	NS	2.8	***	2.4	***	NS	NS	NS	NS	NS	NS	NS
Source * Time	NS	4.0	***	NS	NS	2.8	***	4.8	***	NS	NS	NS
Rate * Time	NS	2.8	***	NS	4.8	***	3.0	***	4.3	***	3.0	3.1

+ Sampling depths (cm)

\* \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Figure 6.57:  $\text{NH}_4^+$  as a function of N source on the high and spring treated plots from the 0 - 60 cm depth in 1993.

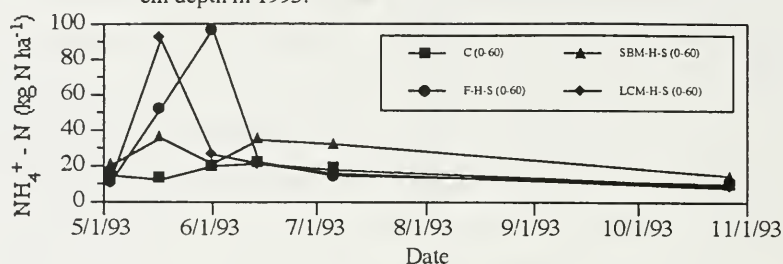


Figure 6.58:  $\text{NH}_4^+$  as a function of N source on the medium and spring treated plots from the 0 - 60 cm depth in 1993.

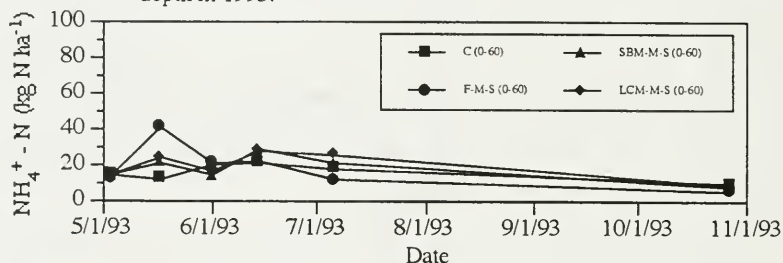


Figure 6.59:  $\text{NH}_4^+$  as a function of N source on the low and spring treated plots from the 0 - 60 cm depth in 1993.

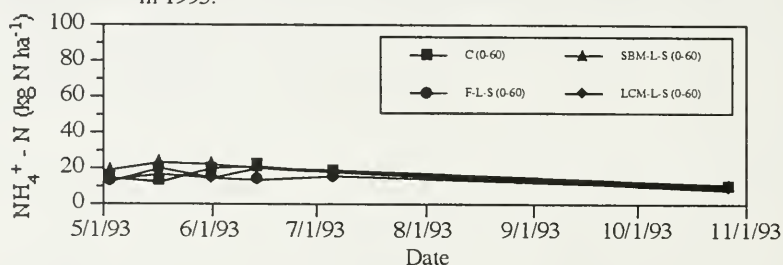


Figure 6.60:  $\text{NH}_4^+$  as a function of N source on the high and fall treated plots from the 0 - 60 cm depth in 1993.

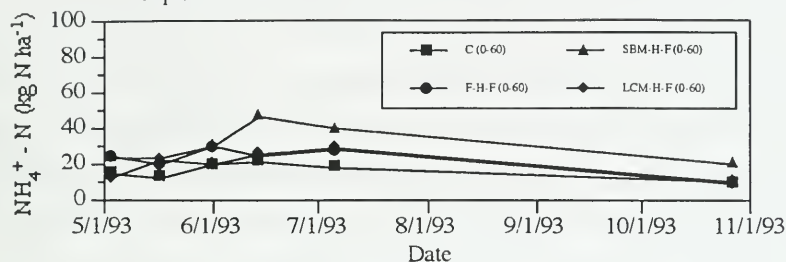


Figure 6.61:  $\text{NH}_4^+$  as a function of N source on the medium and fall treated plots from the 0 - 60 cm depth in 1993.

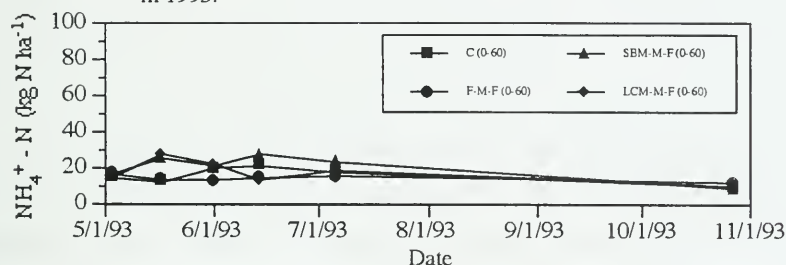
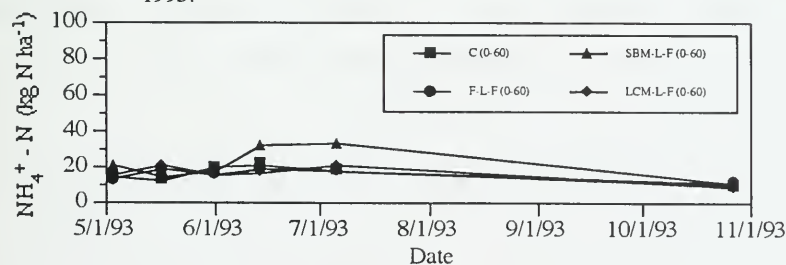


Figure 6.62:  $\text{NH}_4^+$  as a function of N source on the low and fall treated plots from the 0 - 60 cm depth in 1993.



The LCM and  $\text{NH}_4\text{NO}_3$  sources had the highest  $\text{NH}_4^+$  values just after N was applied. However, the LCM reached its peak value at the time of application while the  $\text{NH}_4\text{NO}_3$  source did not reach its peak until the second sampling date after N application. This difference was attributed to the LCM being applied as a liquid which allowed the applied  $\text{NH}_4^+$  to diffuse throughout the soil into which it was incorporated. The  $\text{NH}_4\text{NO}_3$  was applied in pellet form and required some time for the  $\text{NH}_4^+$  to diffuse into the surrounding soil. Both of these sources had measured  $\text{NH}_4^+$  amounts that declined to pre-N application (control plot) values within a month of N application. Again, this was consistent with fast nitrification and low concentrations of  $\text{NH}_4^+$  measured with the solution samplers. The SBM source did not reach the large values after N application as with the other two sources (Figure 6.57). The slight decrease in  $\text{NH}_4^+$  amounts after high rates of SBM application (Figure 6.57) may indicate that short term immobilization was occurring due to the large amounts of added C with the SBM source. However, the SBM values remained higher than the other two sources' values until the October 27 sampling date. This suggested that  $\text{NH}_4^+$  was being mineralized in these plots over the growing season. This short term immobilization and subsequent mineralization throughout the growing season has been observed before (Paul et al., 1991). This was consistent with the idea that the SBM yields were highest in the wet 1992 growing season due to slow release of  $\text{NH}_4^+$ . In contrast, the other two N sources were losing their N via leaching and thus the measured yields were lower. There were negligible differences between N sources at medium and low application rates (Figures 6.58 and 6.59).

Differences between N sources were not as apparent in the fall treated plots. However, it appeared that the SBM source continued to have greater  $\text{NH}_4^+$  amounts than the other two N sources (Figures 6.60 through 6.62). Again, this was most obvious at the high application rates (Figure 6.60). This was consistent with the spring treated plots and was attributed to mineralization of  $\text{NH}_4^+$  from the microbial biomass. Also, note that soil  $\text{NH}_4^+$  values in all treatments return to the control values by the end or beginning of the growing season.

Figure 6.63:  $\text{NH}_4^+$  as a function of N rate on the  $\text{NH}_4\text{NO}_3$  and spring treated plots from the 0 - 60 cm depth in 1993.

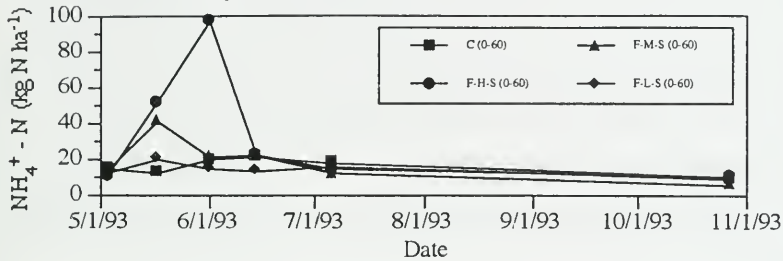


Figure 6.64:  $\text{NH}_4^+$  as a function of N rate on the SBM and spring treated plots from the 0 - 60 cm depth in 1993.

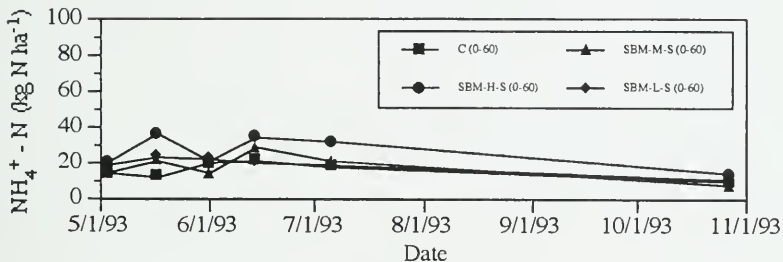
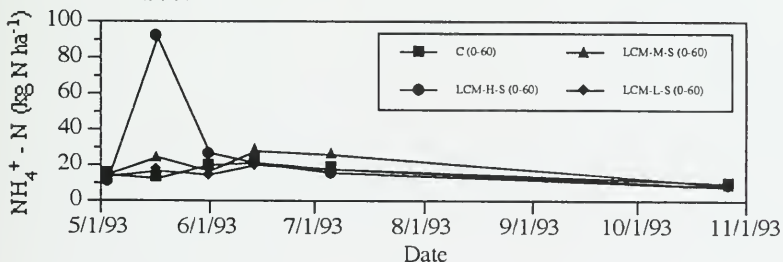


Figure 6.65:  $\text{NH}_4^+$  as a function of N rate on the LCM and spring treated plots from the 0 - 60 cm depth in 1993.



There was a consistent trend, as a function of N application rate, of decreasing soil  $\text{NH}_4^+$  values in the order of high > medium > low for the spring treated plots. However, this trend was only significant in the upper depths of the soil profile (Table 6.9). In addition, the trend was only consistent for the LCM and  $\text{NH}_4\text{NO}_3$  sources within a month of the time of N application. The trend remained consistent for the SBM source over a greater period of time (Figure 6.64). Differences as a function of N rate in fall treated plots were only consistent for the SBM treated plots (Figure 6.67).



Figure 6.66:  $\text{NH}_4^+$  as a function of N rate on the  $\text{NH}_4\text{NO}_3$  and fall treated plots from the 0 - 60 cm depth in 1993.

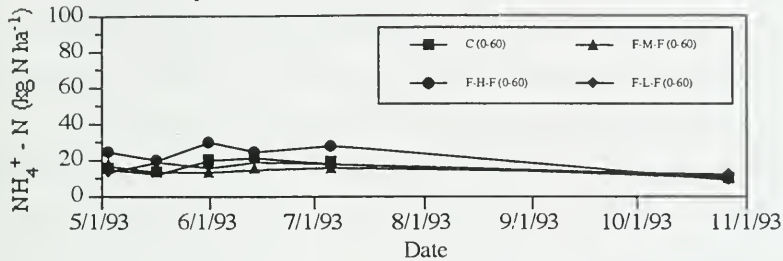


Figure 6.67:  $\text{NH}_4^+$  as a function of N rate on the SBM and fall treated plots from the 0 - 60 cm depth in 1993.

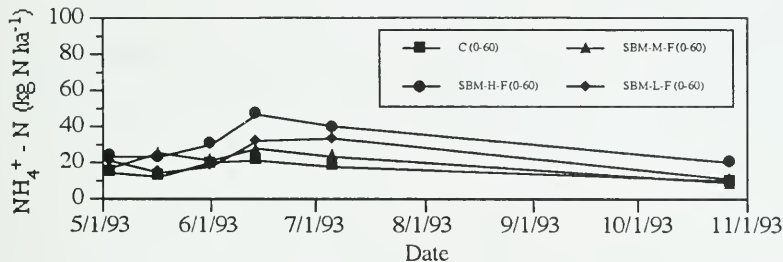
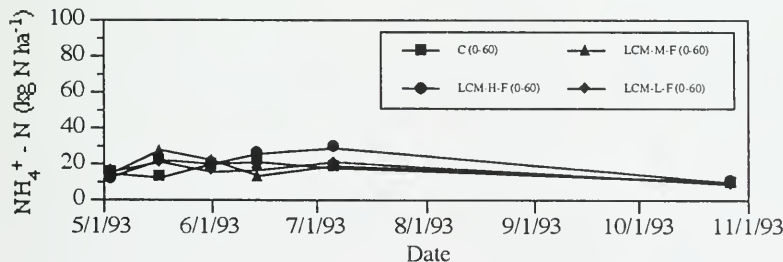


Figure 6.68:  $\text{NH}_4^+$  as a function of N rate on the LCM and fall treated plots from the 0 - 60 cm depth in 1993.



#### 6.4.2 Nitrate Results

The ANOVA F values for the soil  $\text{NO}_3^-$  measurements for the various treatments are given in Table 6.10. N source and N application rate effects were significant at nearly all sampling dates. The influence of plant uptake and leaching on soil  $\text{NO}_3^-$  amounts in the 0 - 15 cm depth was observed by the lack of significant effects on the May 3, 1993 and October 27, 1993 sampling dates (Table 6.10). Significant N application time effects were observed in the 0 - 15 cm depth on each sampling date excluding the October 27, 1993 sampling date. Again, plant uptake and leaching of soil  $\text{NO}_3^-$  out of the 0 - 15 cm depth meant that the significant difference was observed at the 15 - 30 cm depth by harvest time (Table 6.10). Significant interactions were less commonly observed. Nevertheless, consistent trends were observed and figures of the N source with N application time with N application rate interactions will serve as the basis for discussion (Figures 6.69 through 6.152).

Table 6.10: Summary of F values for the various treatments for the 1993 NO<sub>3</sub><sup>-</sup> measurements.

Source of Variation	Sampling Date											
	May 3			May 17			June 1			June 14		
	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60
N Source	2.5	12.4	40.4	3.9	12.8	22.6	18.2	8.4	10.4	15.2	45.6	21.0
N Rate	7.4	19.5	48.8	13.2	13.2	9.9	12.7	24.3	13.6	19.5	9.3	13.0
N Application Time	26.1	109	198	43.4	NS	NS	53.1	5.5	NS	64.6	39.0	3.9
Source * Rate * Time	NS	NS	6.2	NS	NS	NS	NS	NS	NS	7.4	2.7	2.5
Source * Rate	NS	NS	2.1	NS	3.0	NS	NS	3.5	3.1	6.7	3.0	2.7
Source * Time	4.6	15.6	34.6	NS	NS	NS	8.2	NS	NS	11.7	21.4	4.7
Rate * Time	NS	9.0	15.1	NS	NS	NS	NS	NS	NS	6.1	3.7	2.6

+ Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

Figure 6.69:  $\text{NO}_3^-$  on the high and spring treated plots from the 0 - 15 cm depth in 1993.

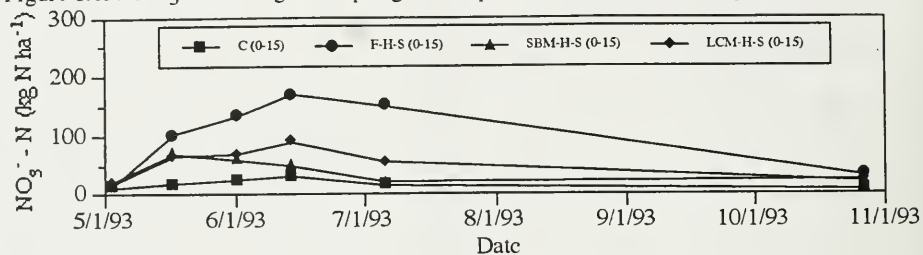


Figure 6.70:  $\text{NO}_3^-$  on the high and spring treated plots from the 15 - 30 cm depth in 1993.

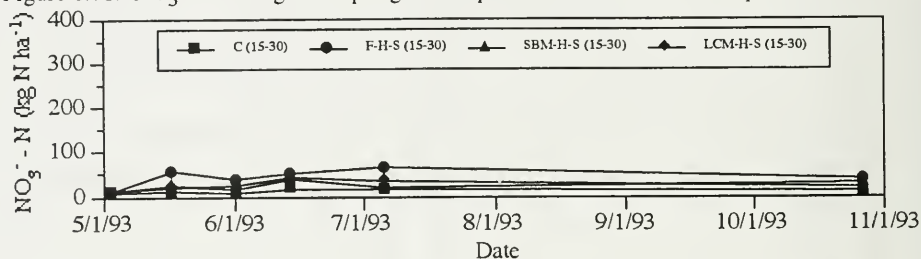


Figure 6.71:  $\text{NO}_3^-$  on the high and spring treated plots from the 30 - 60 cm depth in 1993.

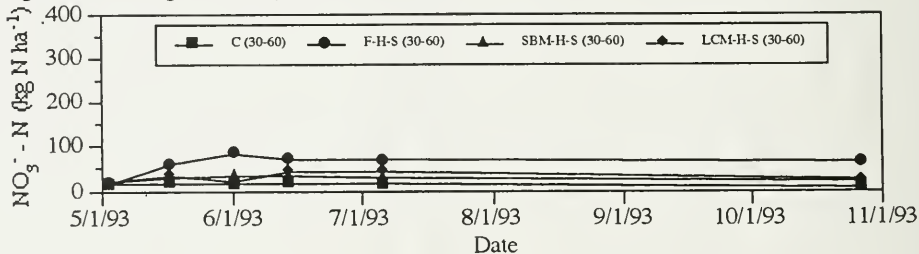


Figure 6.72:  $\text{NO}_3^-$  on the high and spring treated plots from the 0 - 60 cm depth in 1993.

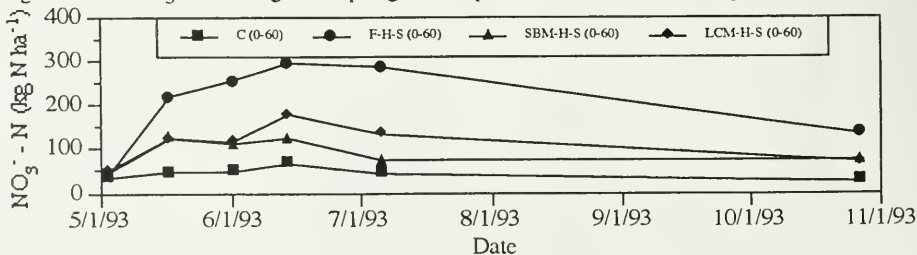


Figure 6.73:  $\text{NO}_3^-$  on the medium and spring treated plots from the 0 - 15 cm depth in 1993.

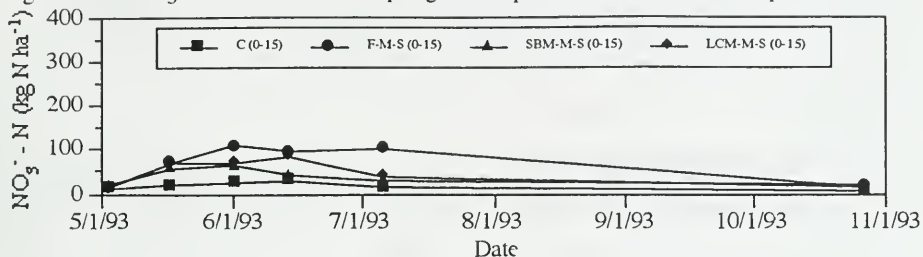


Figure 6.74:  $\text{NO}_3^-$  on the medium and spring treated plots from the 15 - 30 cm depth in 1993.

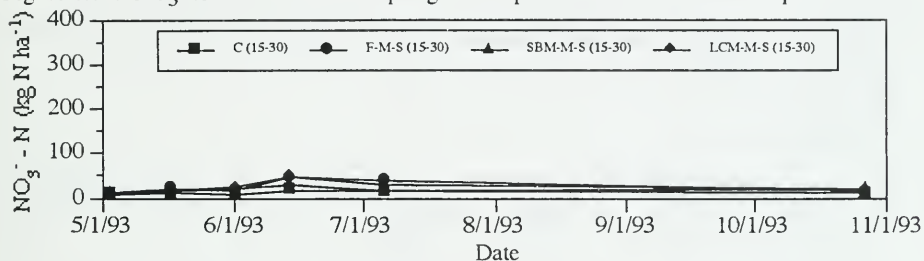


Figure 6.75:  $\text{NO}_3^-$  on the medium and spring treated plots from the 30 - 60 cm depth in 1993.

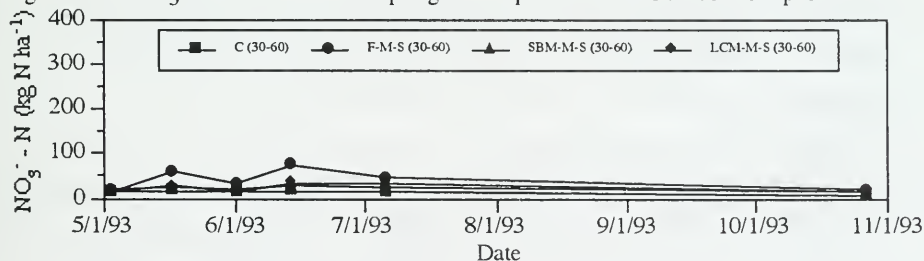


Figure 6.76:  $\text{NO}_3^-$  on the medium and spring treated plots from the 0 - 60 cm depth in 1993.

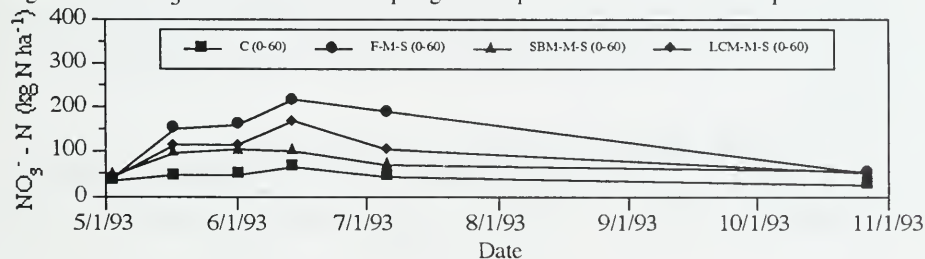


Figure 6.77:  $\text{NO}_3^-$  on the low and spring treated plots from the 0 - 15 cm depth in 1993.

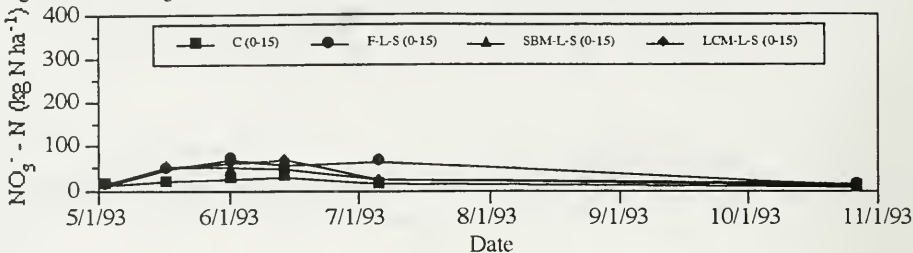


Figure 6.78:  $\text{NO}_3^-$  on the low and spring treated plots from the 15 - 30 cm depth in 1993.

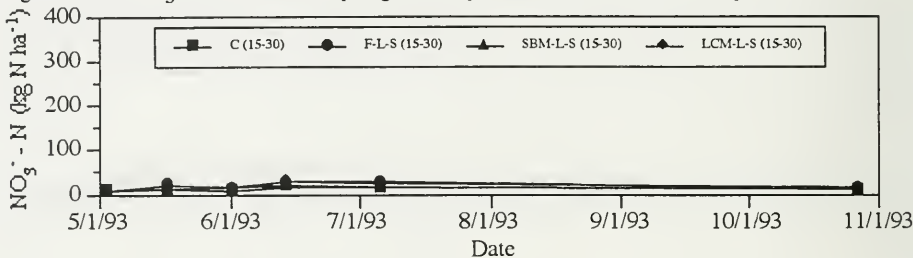


Figure 6.79:  $\text{NO}_3^-$  on the low and spring treated plots from the 30 - 60 cm depth in 1993.

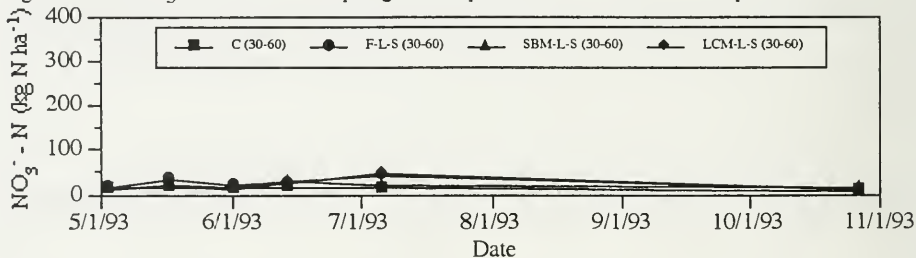
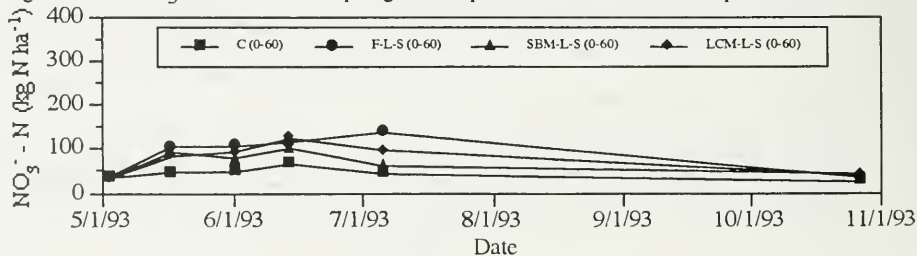


Figure 6.80:  $\text{NO}_3^-$  on the low and spring treated plots from the 0 - 60 cm depth in 1993.



The control plots indicated a slight increase in soil  $\text{NO}_3^-$  over the first three sampling dates which was attributed to mineralization (Figure 6.69). The decrease throughout the rest of the growing season coincides with plant uptake of  $\text{NO}_3^-$ . The largest differences between N sources were observed in the 0 - 15 cm depth for the spring treated plots (Figures 6.69 through 6.80) and in the 30 - 60 cm depth for the fall treated plots (Figures 6.81 through 6.92), respectively. This was consistent with the leaching pattern at this site. When these differences were visible, soil  $\text{NO}_3^-$  amounts followed a decreasing trend in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ . This was consistent with the observed trends measured with the solution samplers. It is interesting to note that the initial soil  $\text{NO}_3^-$  amounts, in the 0 - 60 cm depth, of all three N sources and the control plots were approximately equal on the first sampling date (Figure 6.72). The initial amounts decreased with the N application rate (Figures 6.72, 6.76 and 6.80). However, at the end of the growing season and at the time that leaching begins, there were observed differences between N sources (Table 6.10). The observed differences in  $\text{NO}_3^-$  concentrations, measured with solution samplers, was attributed to the difference in mineral N remaining in the soil profile after harvest. For example, at the high N rate, the difference between the initial soil  $\text{NO}_3^-$  and the fall soil  $\text{NO}_3^-$  values for the  $\text{NH}_4\text{NO}_3$  source (Figure 6.72) was approximately  $100 \text{ kg N ha}^{-1}$ . Assuming a net drainage of 20 cm, a soil solution concentration of  $50 \text{ mg N L}^{-1}$ . The corresponding measured soil solution concentration on December 14, 1993 was approximately  $35 \text{ mg N L}^{-1}$  (Figure 5.35). Considering that the N would be moving as a pulse, as was determined with the  $\text{Cl}^-$  experiments, and that the peak concentration of N would not be expected at the 80 cm depth, these two values agree quite well. Again, this indicated that it is extremely important to determine the actual N requirements of crops and to minimize the amount of soil N in the profile after harvest.

Figure 6.81:  $\text{NO}_3^-$  on the high and fall treated plots from the 0 - 15 cm depth in 1993.

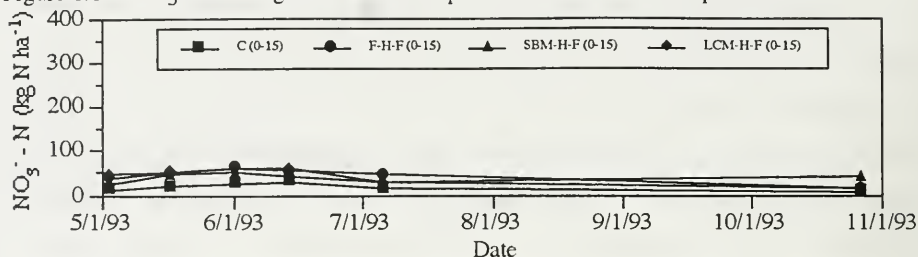


Figure 6.82:  $\text{NO}_3^-$  on the high and fall treated plots from the 15 - 30 cm depth in 1993.

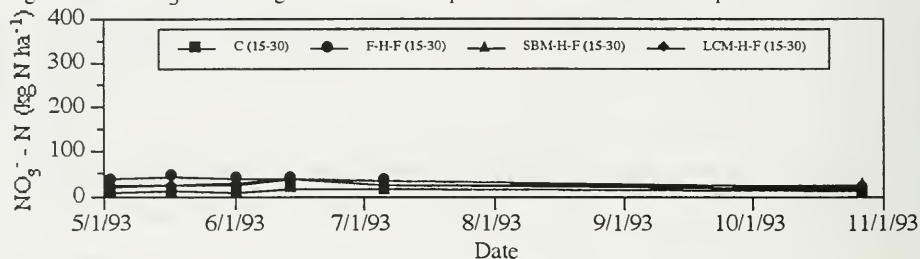


Figure 6.83:  $\text{NO}_3^-$  on the high and fall treated plots from the 30 - 60 cm depth in 1993.

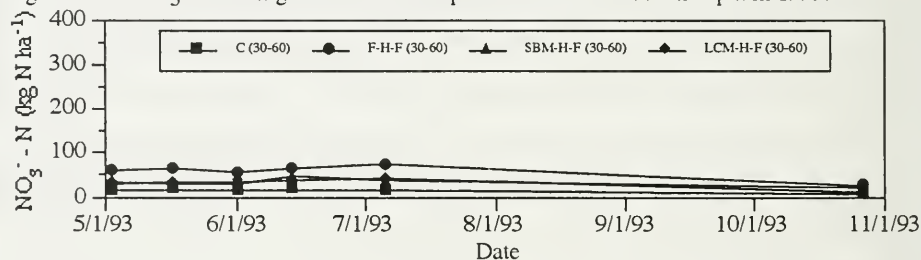


Figure 6.84:  $\text{NO}_3^-$  on the high and fall treated plots from the 0 - 60 cm depth in 1993.

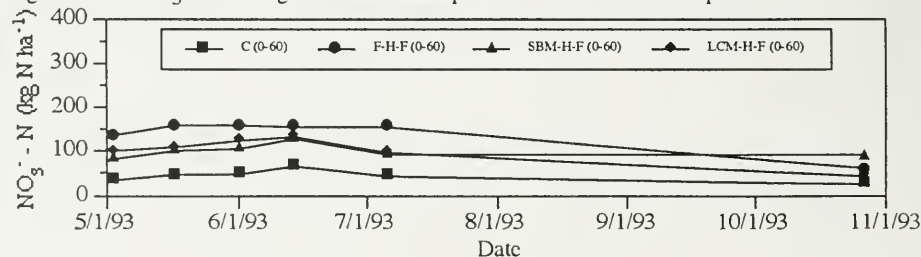




Figure 6.85:  $\text{NO}_3^-$  on the medium and fall treated plots from the 0 - 15 cm depth in 1993.

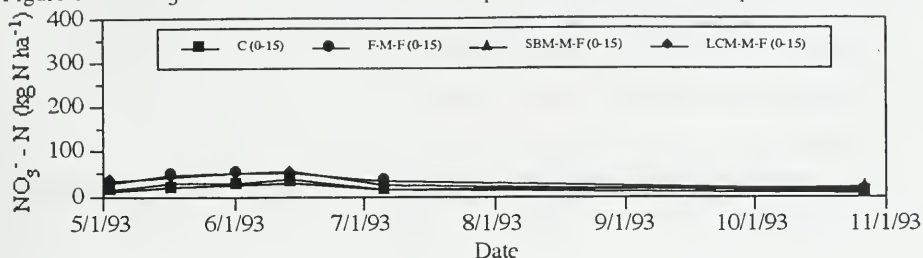


Figure 6.86:  $\text{NO}_3^-$  on the medium and fall treated plots from the 15 - 30 cm depth in 1993.

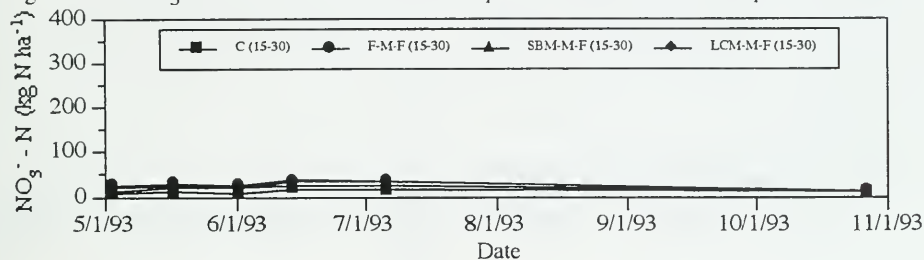


Figure 6.87:  $\text{NO}_3^-$  on the medium and fall treated plots from the 30 - 60 cm depth in 1993.

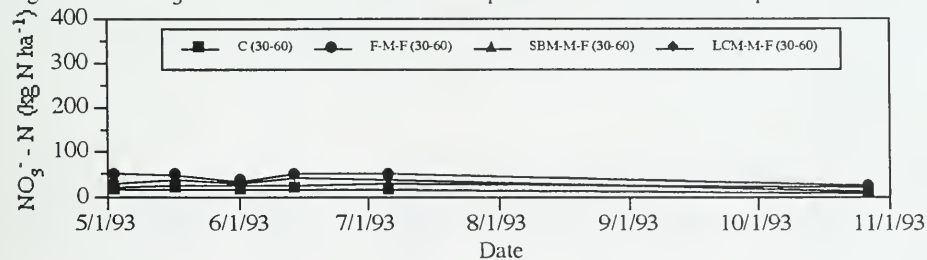


Figure 6.88:  $\text{NO}_3^-$  on the medium and fall treated plots from the 0 - 60 cm depth in 1993.

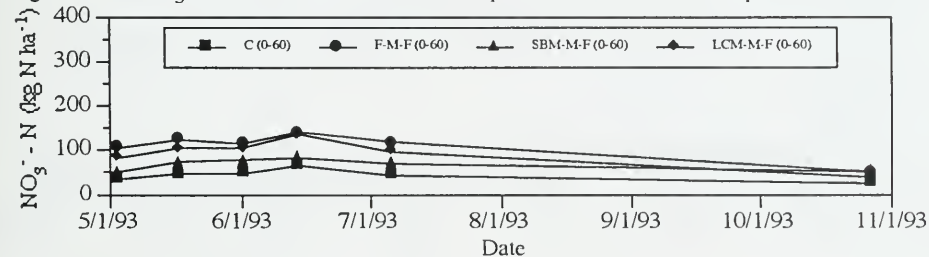


Figure 6.89:  $\text{NO}_3^-$  on the low and fall treated plots from the 0 - 15 cm depth in 1993.

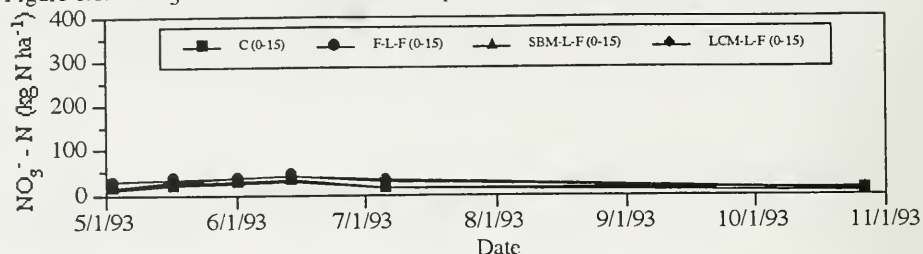


Figure 6.90:  $\text{NO}_3^-$  on the low and fall treated plots from the 15 - 30 cm depth in 1993.

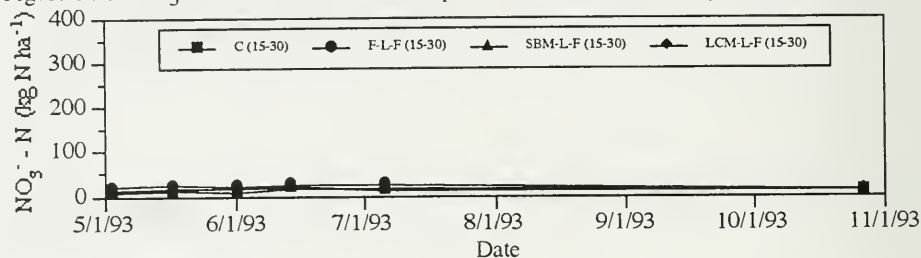


Figure 6.91:  $\text{NO}_3^-$  on the low and fall treated plots from the 30 - 60 cm depth in 1993.

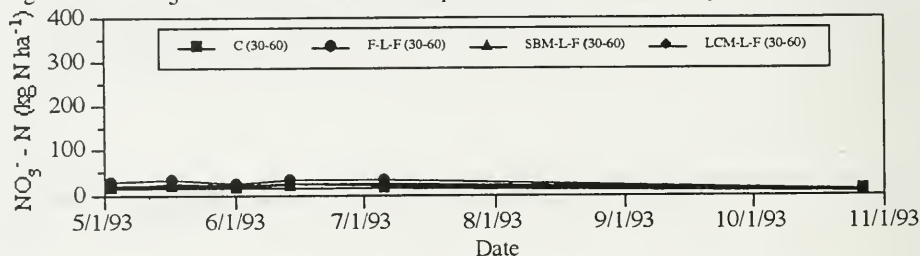
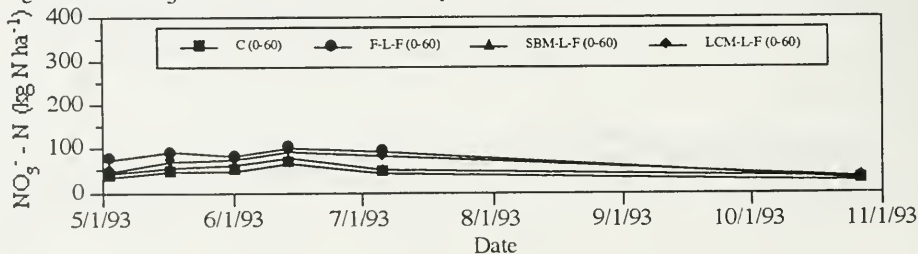


Figure 6.92:  $\text{NO}_3^-$  on the low and fall treated plots from the 0 - 60 cm depth in 1993.



The influence of N application rate was most obvious on the spring treated plots and at the 0 - 15 cm depth (Figures 6.93 through 6.116). This was consistent with the low amounts of net drainage throughout the growing season. In addition, the largest differences between N rates were observed in the  $\text{NH}_4\text{NO}_3$  treated plots (Figures 6.93 through 6.96). In general, there was a decreasing trend in soil  $\text{NO}_3^-$  amounts in the order of high > medium > low. Again, this was consistent with the observed solution sampler data (Chapter 5).

As expected, fall treated plots had higher soil  $\text{NO}_3^-$  amounts than the spring treated plots prior to the spring applications (Figures 6.117 through 6.152). However, the difference was at the 30 - 60 cm depth which was consistent with leaching data (Chapter 5) but this also means that some of this N is too deep to be available to the plants when they need it most. The reduced yields of the fall treated plots, relative to the spring treated plots appears to substantiate this. Again, differences between N application times are N application rate and N source dependent.

Figure 6.93:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and spring treated plots from the 0 - 15 cm depth in 1993.

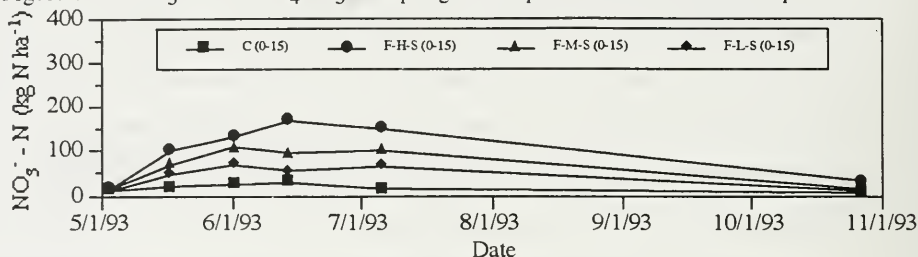


Figure 6.94:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and spring treated plots from the 15 - 30 cm depth in 1993.

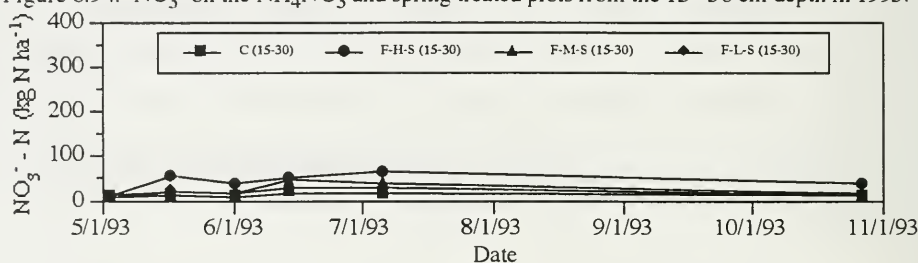


Figure 6.95:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and spring treated plots from the 30 - 60 cm depth in 1993.

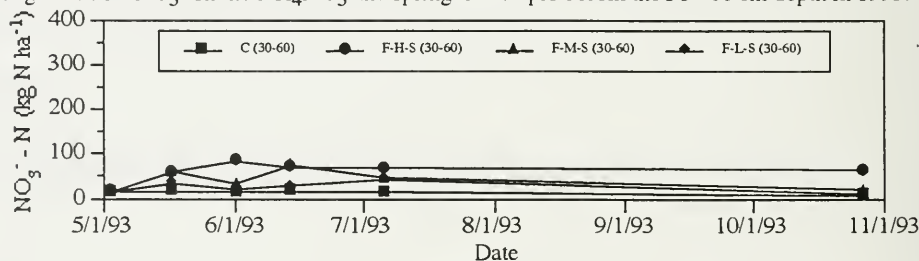


Figure 6.96:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and spring treated plots from the 0 - 60 cm depth in 1993.

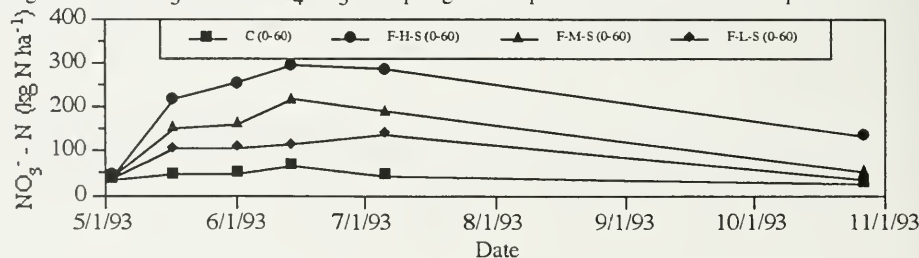


Figure 6.97:  $\text{NO}_3^-$  on the SBM and spring treated plots from the 0 - 15 cm depth in 1993.

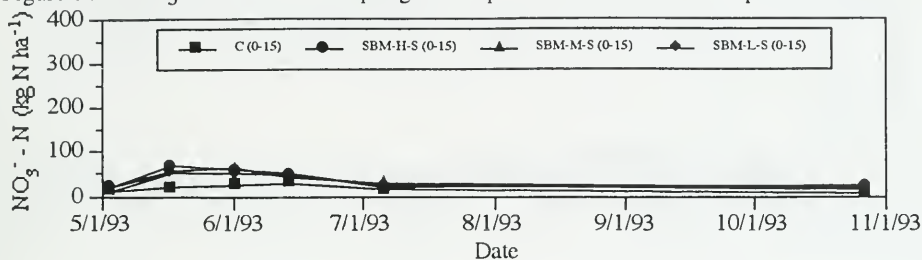


Figure 6.98:  $\text{NO}_3^-$  on the SBM and spring treated plots from the 15 - 30 cm depth in 1993.

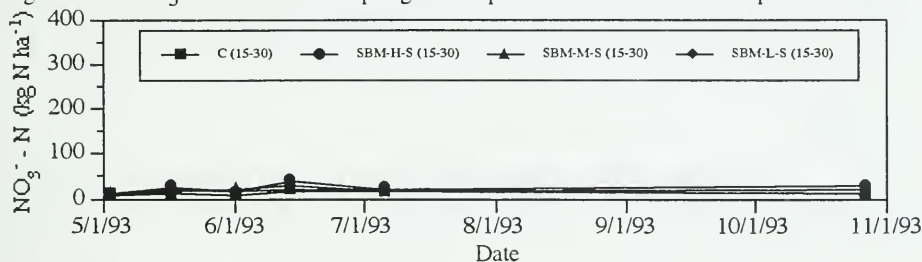


Figure 6.99:  $\text{NO}_3^-$  on the SBM and spring treated plots from the 30 - 60 cm depth in 1993.

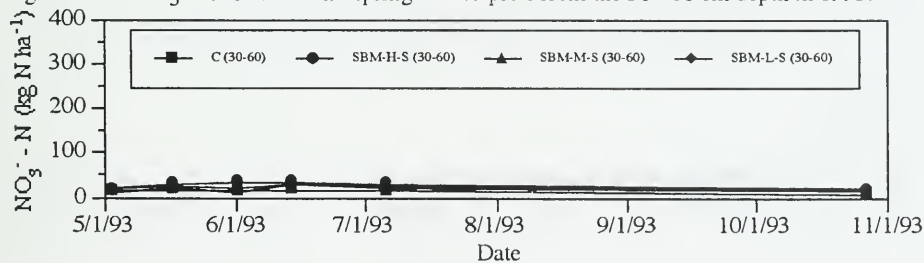


Figure 6.100:  $\text{NO}_3^-$  on the SBM and spring treated plots from the 0 - 60 cm depth in 1993.

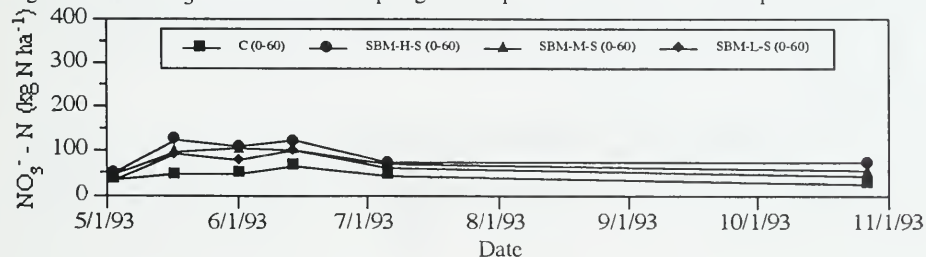


Figure 6.101:  $\text{NO}_3^-$  on the LCM and spring treated plots from the 0 - 15 cm depth in 1993.

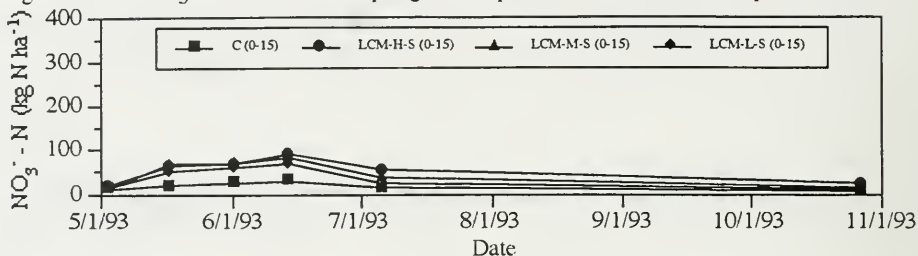


Figure 6.102:  $\text{NO}_3^-$  on the LCM and spring treated plots from the 15 - 30 cm depth in 1993.

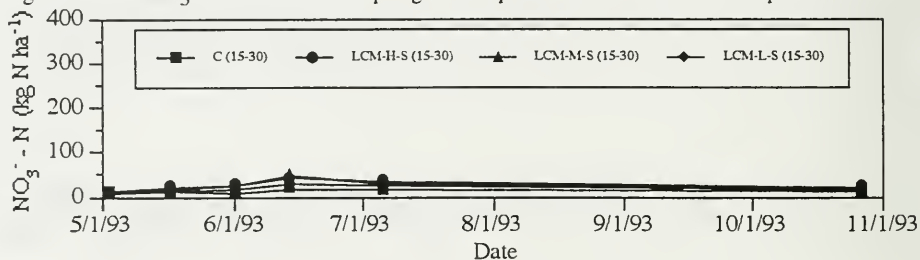


Figure 6.103:  $\text{NO}_3^-$  on the LCM and spring treated plots from the 30 - 60 cm depth in 1993.

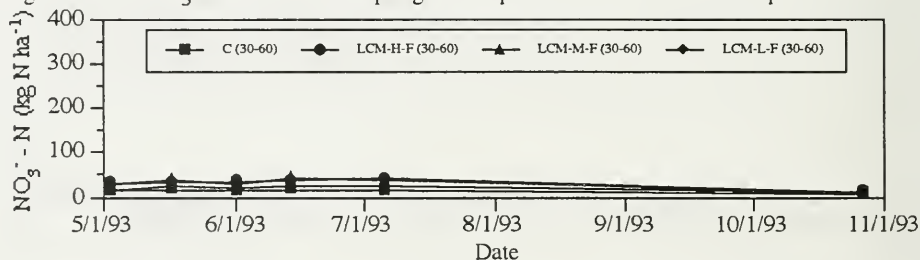


Figure 6.104:  $\text{NO}_3^-$  on the LCM and spring treated plots from the 0 - 60 cm depth in 1993.

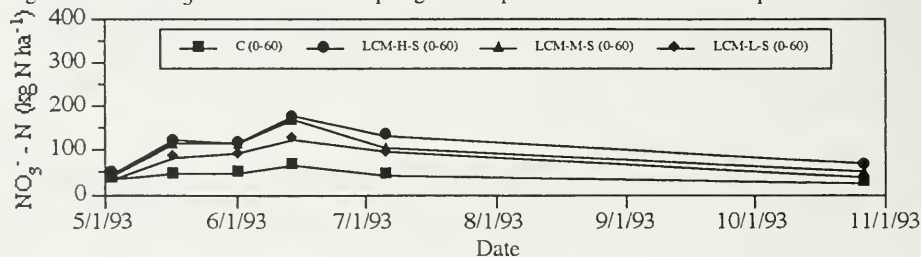


Figure 6.105:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and fall treated plots from the 0 - 15 cm depth in 1993.

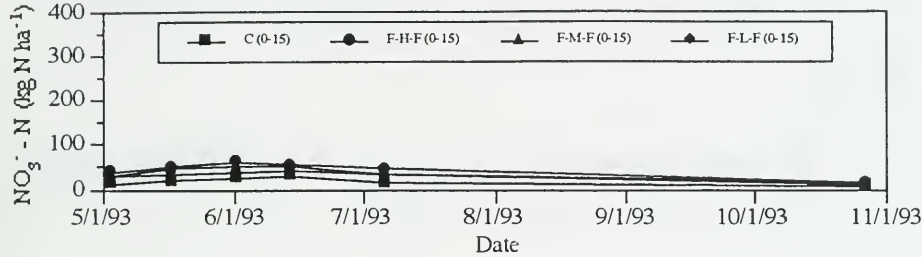


Figure 6.106:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and fall treated plots from the 15 - 30 cm depth in 1993.

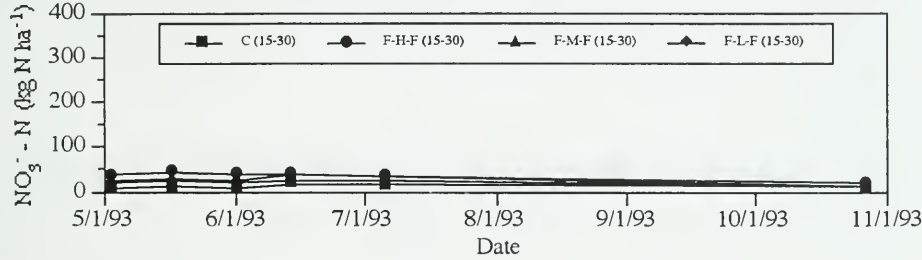


Figure 6.107:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and fall treated plots from the 30 - 60 cm depth in 1993.

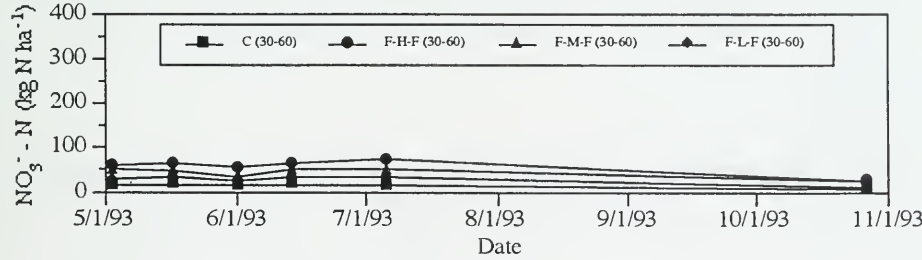


Figure 6.108:  $\text{NO}_3^-$  on the  $\text{NH}_4\text{NO}_3$  and fall treated plots from the 0 - 60 cm depth in 1993.

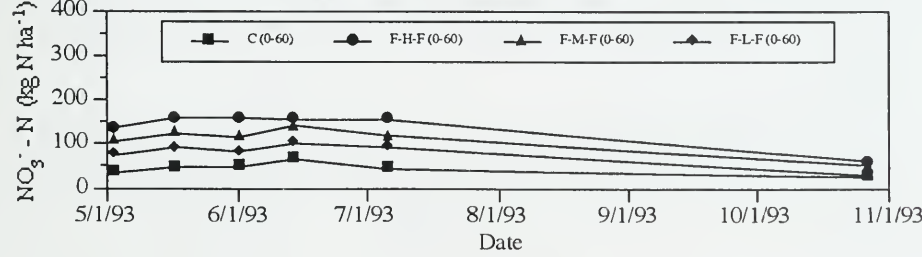


Figure 6.109:  $\text{NO}_3^-$  on the SBM and fall treated plots from the 0 - 15 cm depth in 1993.

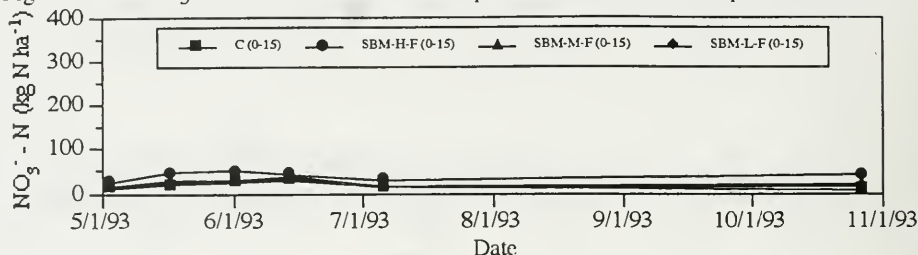


Figure 6.110:  $\text{NO}_3^-$  on the SBM and fall treated plots from the 15 - 30 cm depth in 1993.

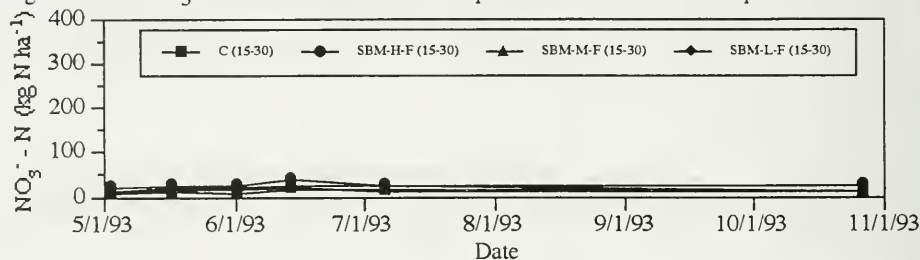


Figure 6.111:  $\text{NO}_3^-$  on the SBM and fall treated plots from the 30 - 60 cm depth in 1993.

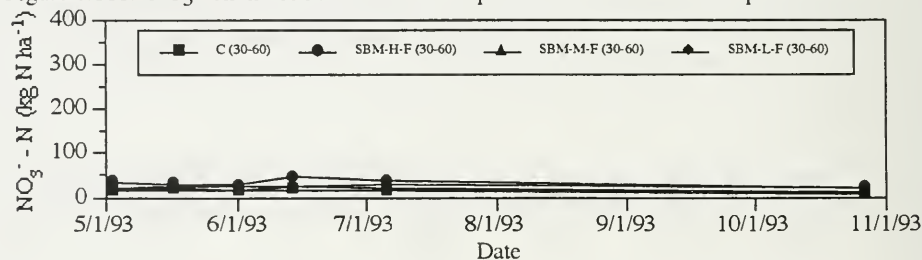


Figure 6.112:  $\text{NO}_3^-$  on the SBM and fall treated plots from the 0 - 60 cm depth in 1993.

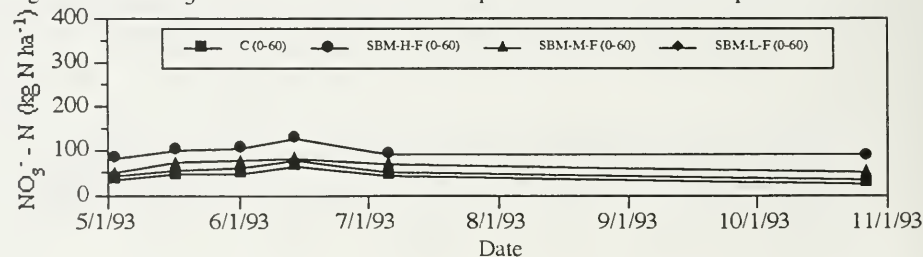




Figure 6.113:  $\text{NO}_3^-$  on the LCM and fall treated plots from the 0 - 15 cm depth in 1993.

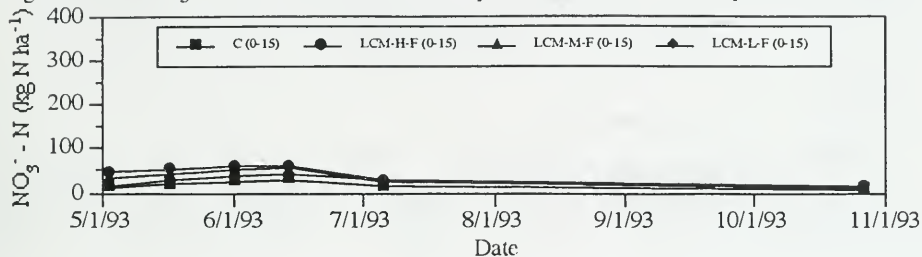


Figure 6.114:  $\text{NO}_3^-$  on the LCM and fall treated plots from the 15 - 30 cm depth in 1993.

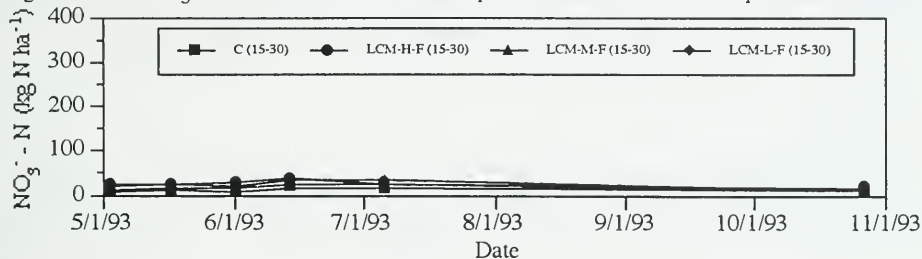


Figure 6.115:  $\text{NO}_3^-$  on the LCM and fall treated plots from the 30 - 60 cm depth in 1993.

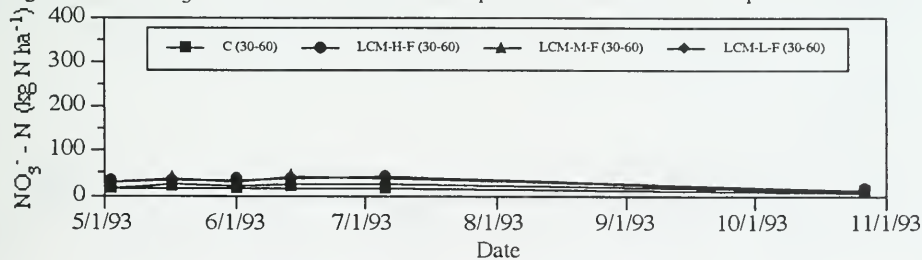


Figure 6.116:  $\text{NO}_3^-$  on the LCM and fall treated plots from the 0 - 60 cm depth in 1993.

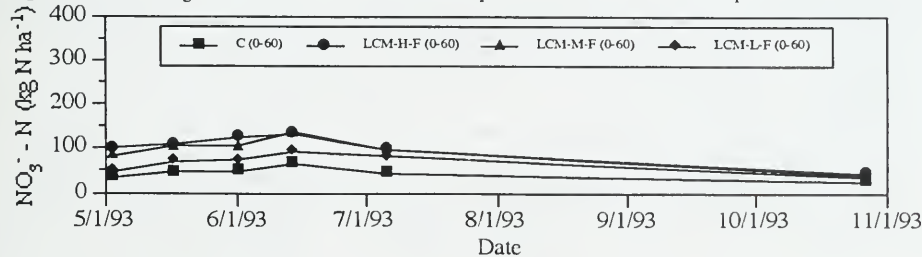


Figure 6.117:  $\text{NO}_3^-$  on the high rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 15 cm depth in 1993.

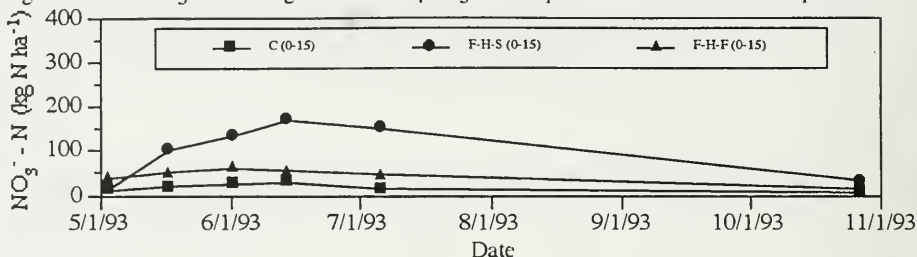


Figure 6.118:  $\text{NO}_3^-$  on the high rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 15 - 30 cm depth in 1993.

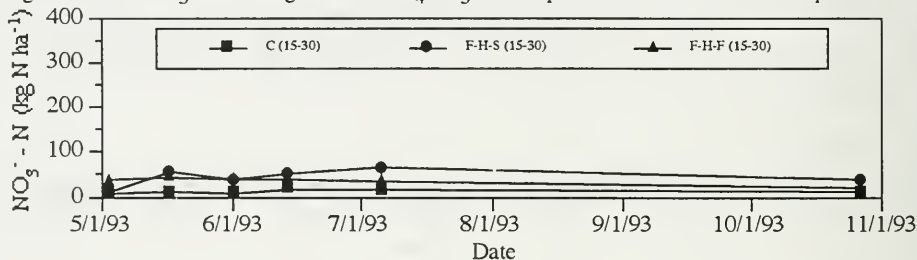


Figure 6.119:  $\text{NO}_3^-$  on the high rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 30 - 60 cm depth in 1993.

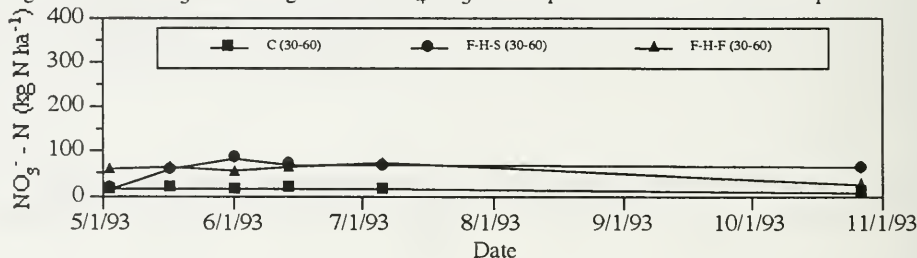


Figure 6.120:  $\text{NO}_3^-$  on the high rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 60 cm depth in 1993.

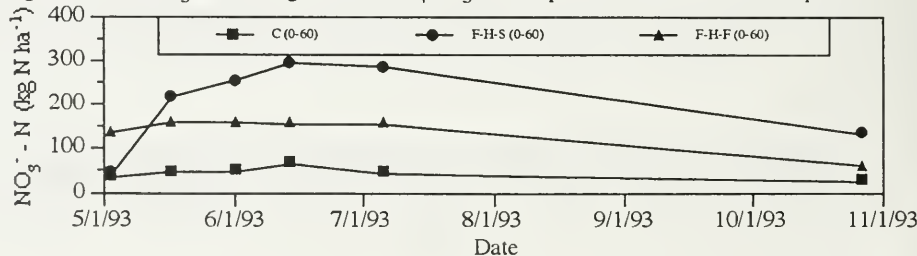


Figure 6.121:  $\text{NO}_3^-$  on the medium rate  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 15 cm depth in 1993.

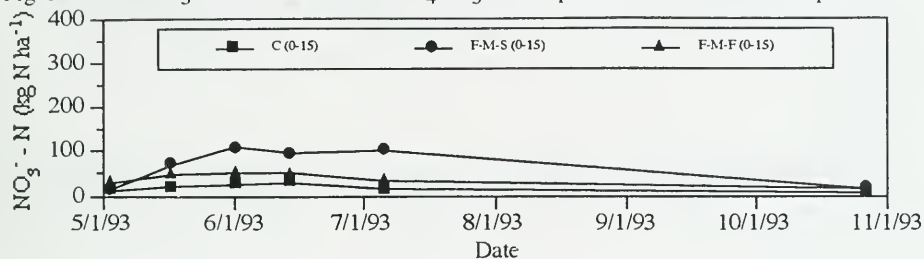


Figure 6.122:  $\text{NO}_3^-$  on the medium rate  $\text{NH}_4\text{NO}_3$  treated plots from the 15 - 30 cm depth in 1993.

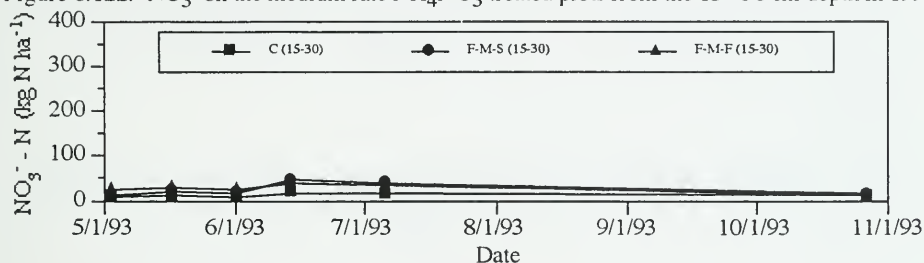


Figure 6.123:  $\text{NO}_3^-$  on the medium rate  $\text{NH}_4\text{NO}_3$  treated plots from the 30 - 60 cm depth in 1993.

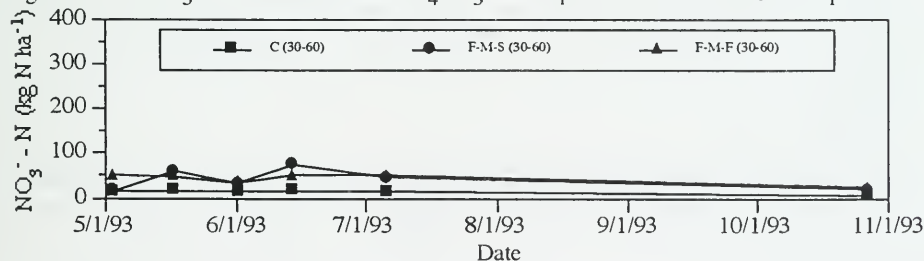


Figure 6.124:  $\text{NO}_3^-$  on the medium rate  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 60 cm depth in 1993.

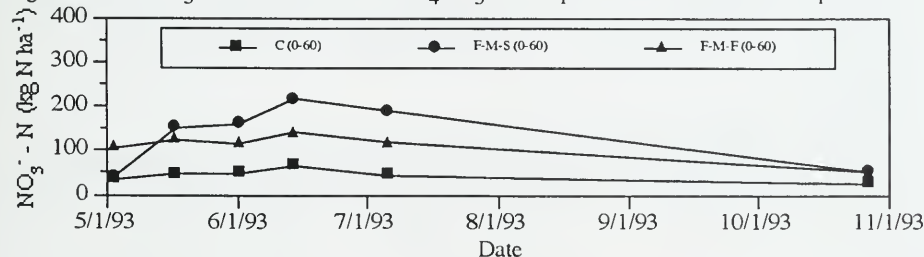


Figure 6.125:  $\text{NO}_3^-$  on the low rate  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 15 cm depth in 1993.

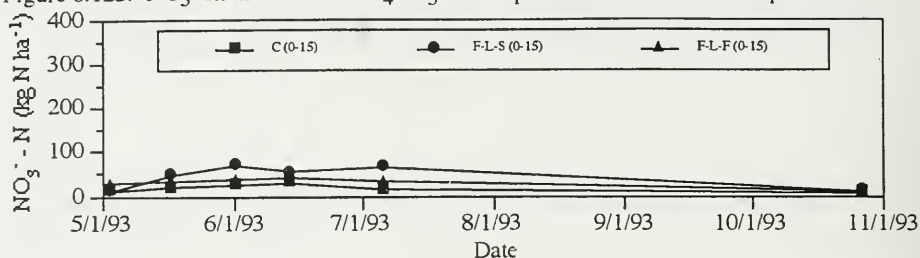


Figure 6.126:  $\text{NO}_3^-$  on the low rate  $\text{NH}_4\text{NO}_3$  treated plots from the 15 - 30 cm depth in 1993.

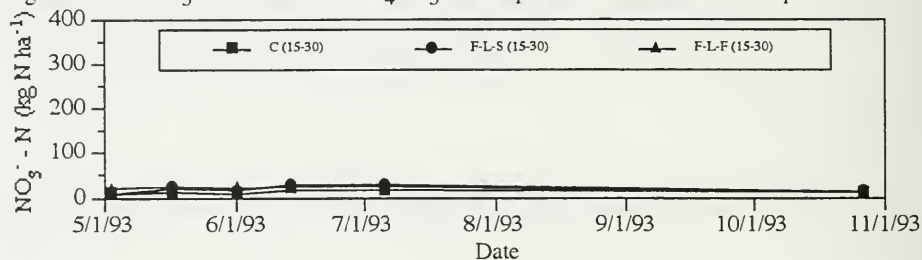


Figure 6.127:  $\text{NO}_3^-$  on the low rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 30 - 60 cm depth in 1993.

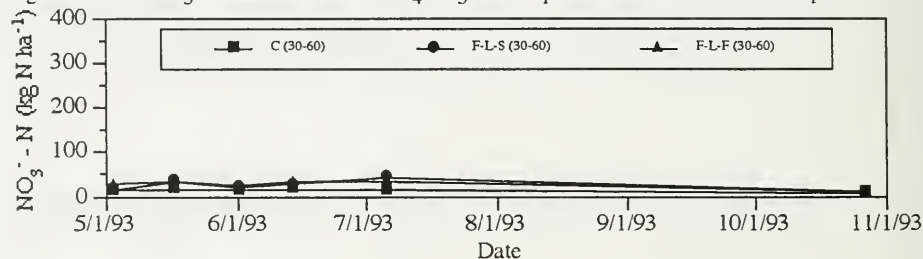


Figure 6.128:  $\text{NO}_3^-$  on the low rate of  $\text{NH}_4\text{NO}_3$  treated plots from the 0 - 60 cm depth in 1993.

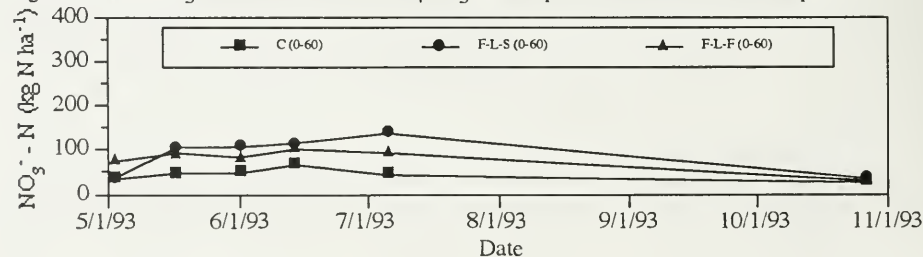


Figure 6.129:  $\text{NO}_3^-$  on the high rate SBM treated plots from the 0 - 15 cm depth in 1993.

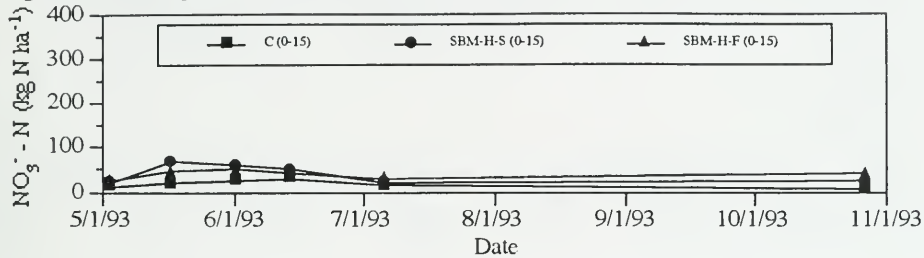


Figure 6.130:  $\text{NO}_3^-$  on the high rate SBM treated plots from the 15 - 30 cm depth in 1993.

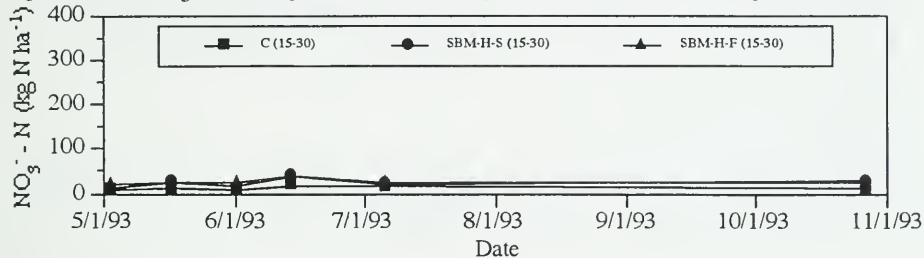


Figure 6.131:  $\text{NO}_3^-$  on the high rate SBM treated plots from the 30 - 60 cm depth in 1993.

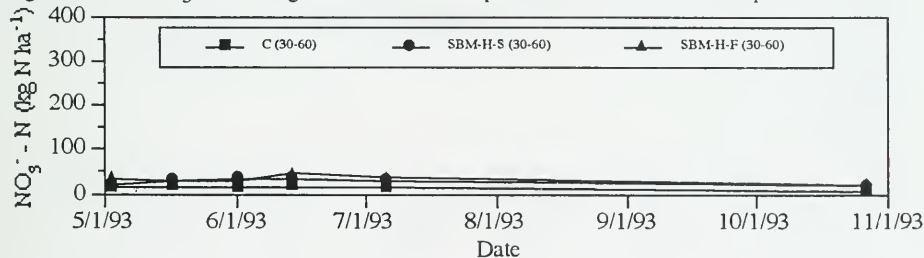


Figure 6.132:  $\text{NO}_3^-$  on the high rate SBM treated plots from the 0 - 60 cm depth in 1993.

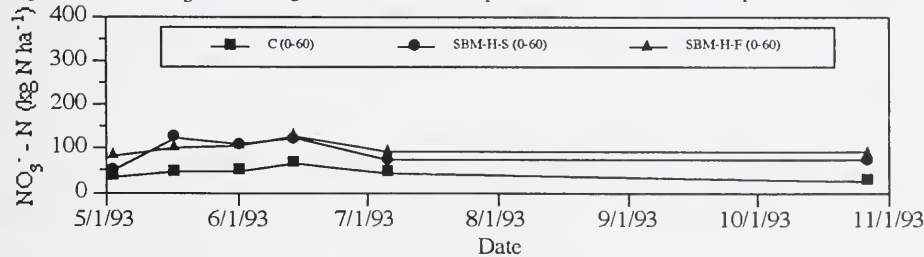


Figure 6.133:  $\text{NO}_3^-$  on the medium rate SBM treated plots from the 0 - 15 cm depth in 1993.

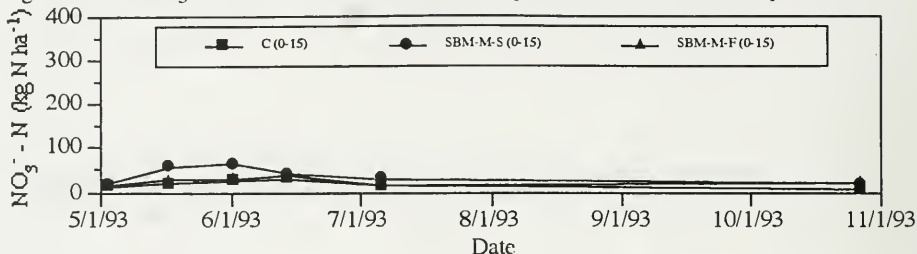


Figure 6.134:  $\text{NO}_3^-$  on the medium rate SBM treated plots from the 15 - 30 cm depth in 1993.

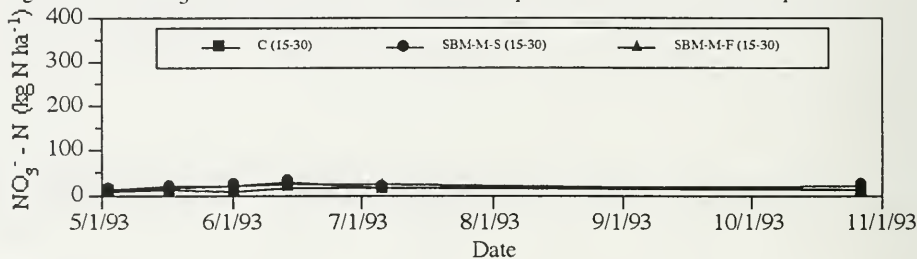


Figure 6.135:  $\text{NO}_3^-$  on the medium rate SBM treated plots from the 30 - 60 cm depth in 1993.

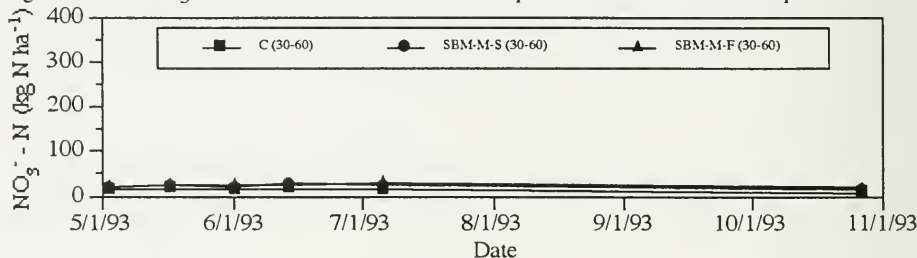


Figure 6.136:  $\text{NO}_3^-$  on the medium rate SBM treated plots from the 0 - 60 cm depth in 1993.

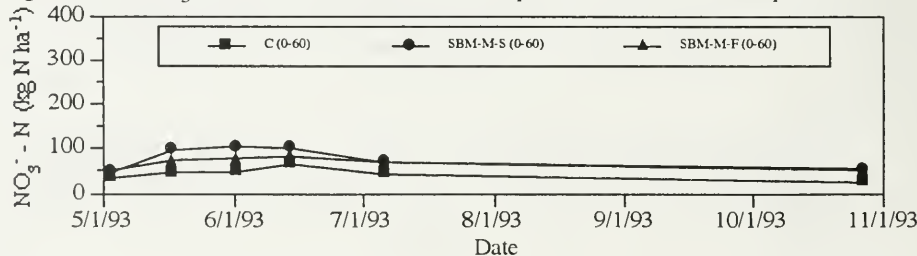


Figure 6.137:  $\text{NO}_3^-$  on the low rate SBM treated plots from the 0 - 15 cm depth in 1993.

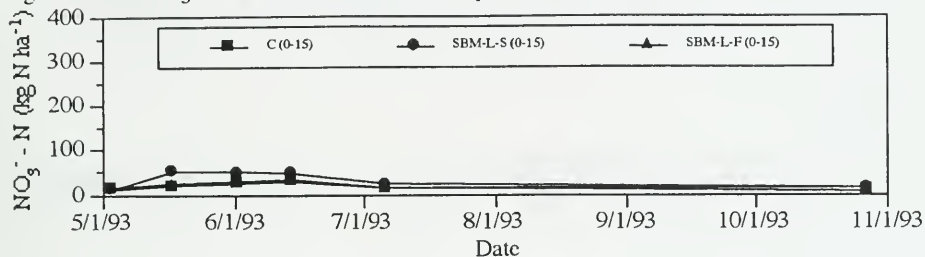


Figure 6.138:  $\text{NO}_3^-$  on the low rate SBM treated plots from the 15 - 30 cm depth in 1993.

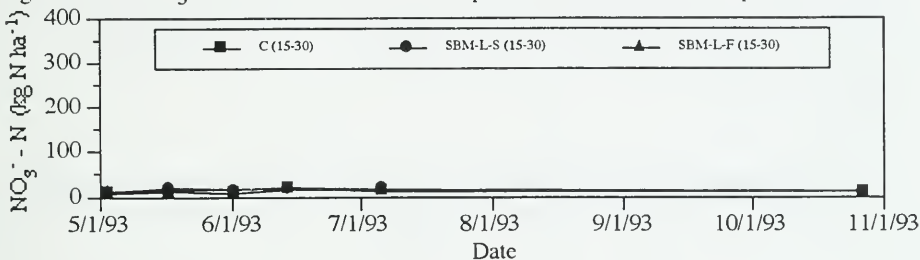


Figure 6.139:  $\text{NO}_3^-$  on the low rate SBM treated plots from the 30 - 60 cm depth in 1993.

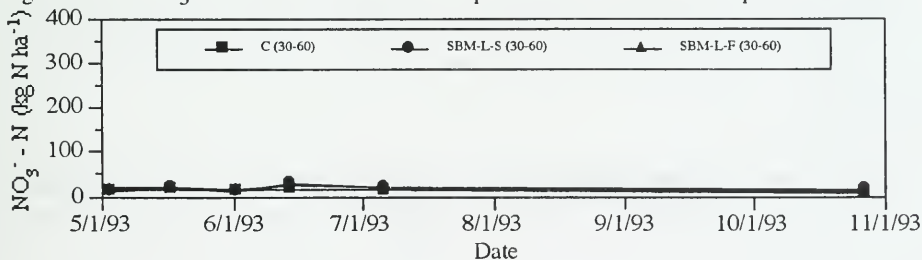


Figure 6.140:  $\text{NO}_3^-$  on the low rate SBM treated plots from the 0 - 60 cm depth in 1993.

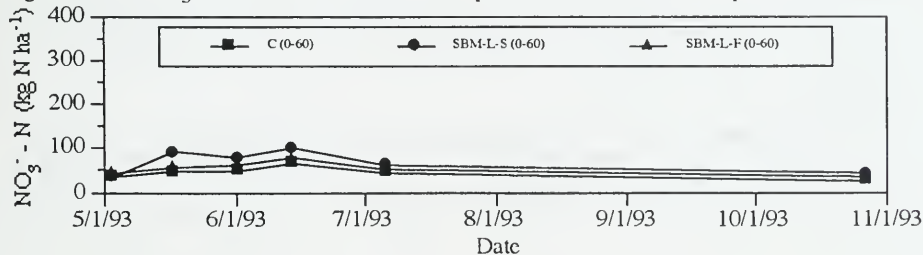


Figure 6.141:  $\text{NO}_3^-$  on the high rate LCM treated plots from the 0 - 15 cm depth in 1993.

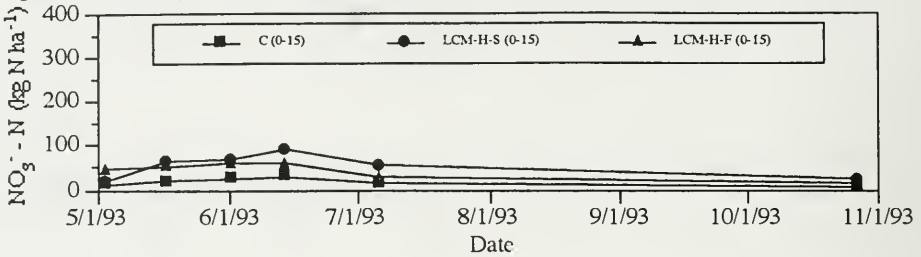


Figure 6.142:  $\text{NO}_3^-$  on the high rate LCM treated plots from the 15 - 30 cm depth in 1993.

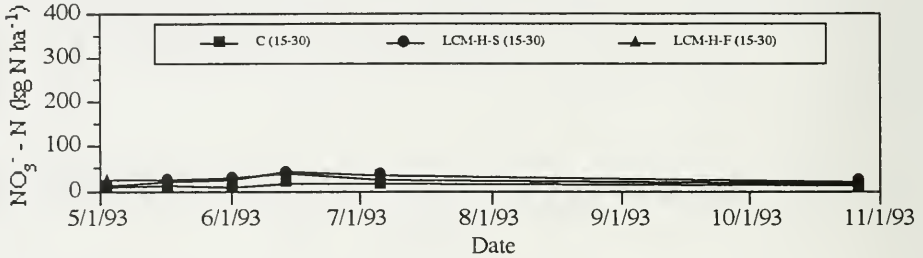


Figure 6.143:  $\text{NO}_3^-$  on the high rate LCM treated plots from the 30 - 60 cm depth in 1993.

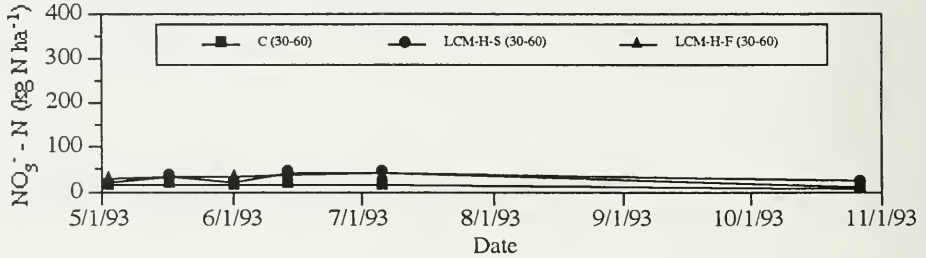


Figure 6.144:  $\text{NO}_3^-$  on the high rate LCM treated plots from the 0 - 60 cm depth in 1993.

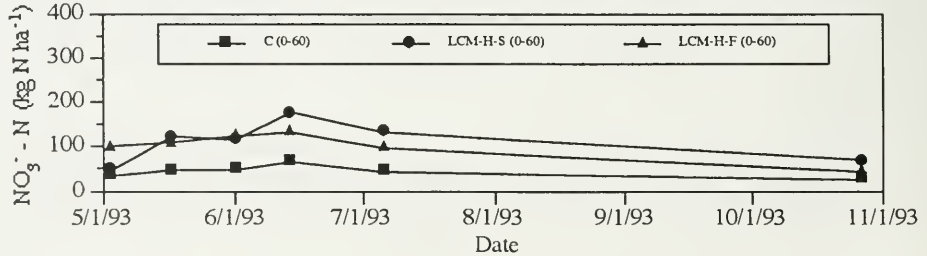




Figure 6.145:  $\text{NO}_3^-$  on the medium rate LCM treated plots from the 0 - 15 cm depth in 1993.

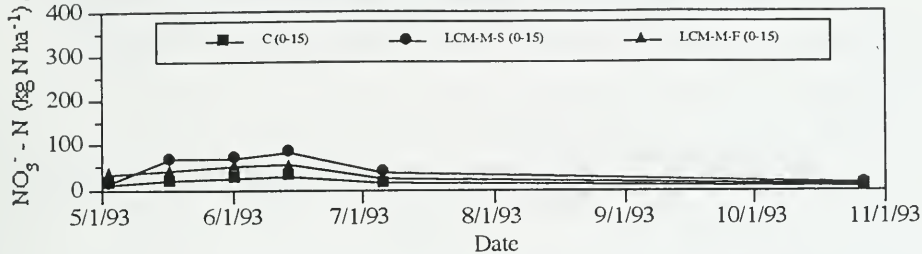


Figure 6.146:  $\text{NO}_3^-$  on the medium rate LCM treated plots from the 15 - 30 cm depth in 1993.

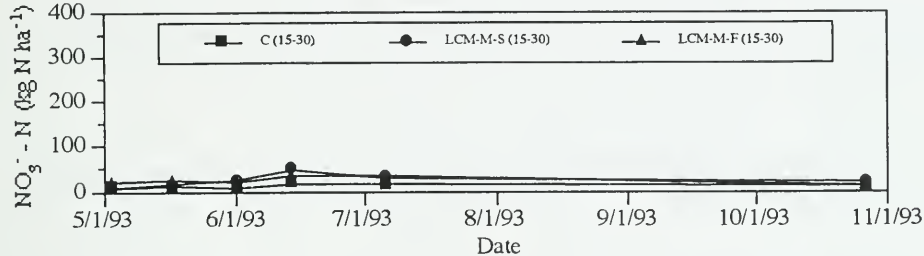


Figure 6.147:  $\text{NO}_3^-$  on the medium rate LCM treated plots from the 30 - 60 cm depth in 1993.

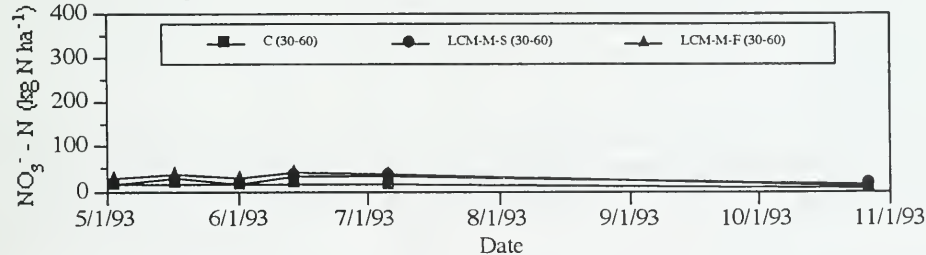


Figure 6.148:  $\text{NO}_3^-$  on the medium rate LCM treated plots from the 0 - 60 cm depth in 1993.

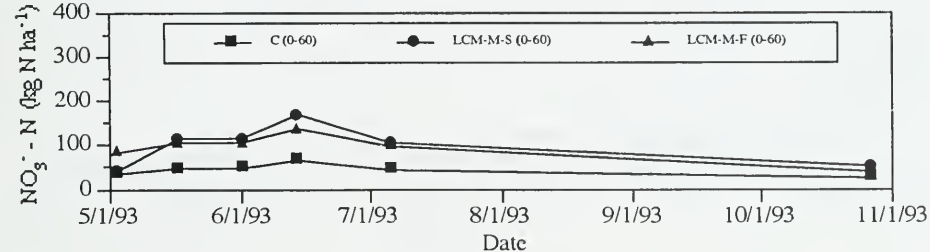


Figure 6.149:  $\text{NO}_3^-$  on the low rate LCM treated plots from the 0 - 15 cm depth in 1993.

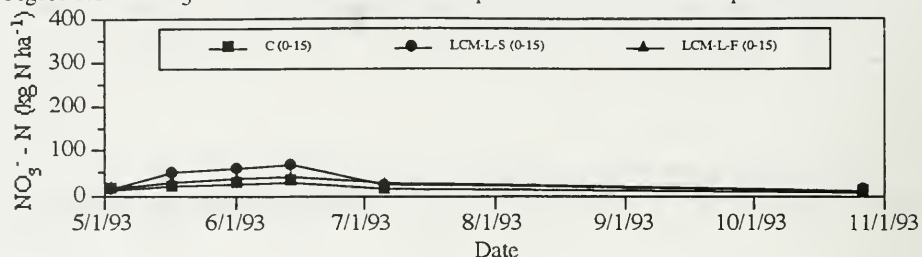


Figure 6.150:  $\text{NO}_3^-$  on the low rate LCM treated plots from the 15 - 30 cm depth in 1993.

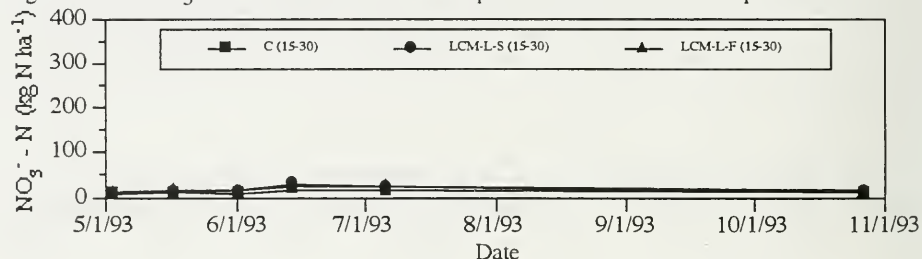


Figure 6.151:  $\text{NO}_3^-$  on the low rate LCM treated plots from the 30 - 60 cm depth in 1993.

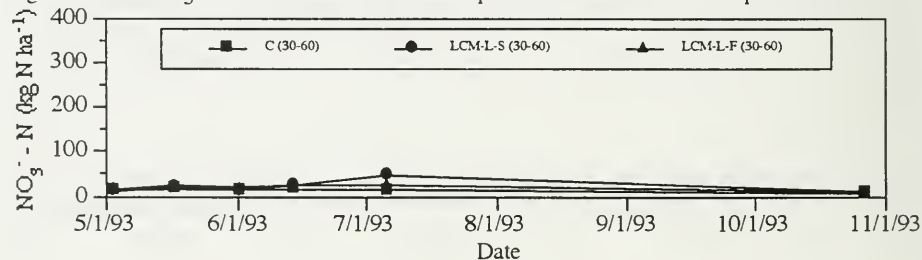
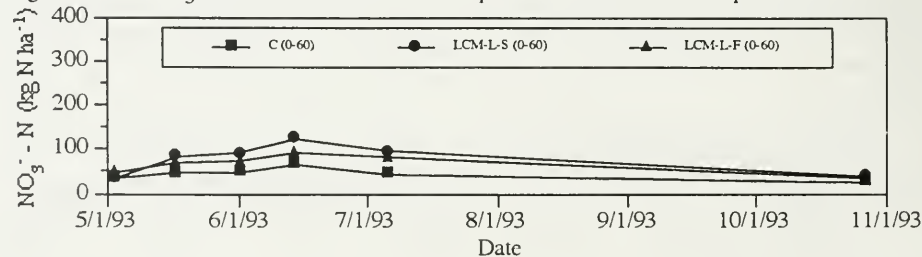


Figure 6.152:  $\text{NO}_3^-$  on the low rate LCM treated plots from the 0 - 60 cm depth in 1993.



## 6.5 Combined CHCl<sub>3</sub>-extractable N and C Results for 1991, 1992 and 1993

Differences within 1992 and 1993 are difficult to observe since only one measurement date in 1992 and 1993 was made. The ANOVA F values for the 1992 sampling date was given in Table 6.6 and 6.11 gives similar values for the July 6, 1993 sampling date. Fewer significant differences were observed in 1993 as in 1991 and 1992. Differences between treatments, over the three years, will be presented in the next two sections. Due to the lack of significant differences, the means of the various treatments will be presented as was done for the 1991 CHCl<sub>3</sub>-extractable N and C data.

Table 6.11: Summary of F values for the various treatments for the 1993 CHCl<sub>3</sub>-extractable N and C measurements made on July 6, 1993.

Source of Variation	CHCl <sub>3</sub> -extractable N			CHCl <sub>3</sub> -extractable C		
	0 - 15 <sup>+</sup>	15 - 30	30 - 60	0 - 15	15 - 30	30 - 60
N Source	4.0 <sup>**</sup>	NS	NS	NS	NS	NS
N Application Rate	NS	NS	NS	NS	NS	NS
N Application Time	NS	NS	NS	10.9 <sup>***</sup>	9.7 <sup>***</sup>	NS
Source*Rate*Time	NS	NS	NS	NS	NS	NS
Source*Rate	NS	NS	NS	NS	NS	NS
Source*Time	NS	NS	NS	NS	NS	NS
Rate * Source	NS	NS	NS	NS	NS	NS

<sup>+</sup> Sampling depths (cm)

\*, \*\*, \*\*\* Significant at a probability level of 0.10, 0.05 and 0.01, respectively.

NS - not significant

ND - measurement not done

CHCl<sub>3</sub>-extractable N and C data are not shown since only two sets of samples were taken and a significant difference was observed in 1992 only (Tables (6.6 and 6.11). In general, CHCl<sub>3</sub>-extractable C and N values exhibited similar trends as soil mineral N. Spring treated plots had amounts of each that were greater than the fall treated plots from the 0 - 30 cm depth but the opposite was true at the 30 - 60 cm depth. Again, considering the leaching pattern at this site and the measurement times, this would seem appropriate.

At all depths and for all N sources,  $\text{CHCl}_3$ -extractable N values increased from 1991 to 1992 and then decreased slightly to 1993 (Figures 6.153 through 6.156). This was also true for the control plots. Although there was little difference between N sources at each depth, over the 0 - 60 cm depth, it appeared as though the SBM source had larger  $\text{CHCl}_3$ -extractable N values than the other N sources (Figure 6.156). This was consistent with previous research that has indicated larger microbial populations after soil incorporation of solid manures. When averaged over N application time and N source, little difference was observed between the various N application rates (Figures 6.157 through 6.160).

Similar results were observed with the  $\text{CHCl}_3$ -extractable C values (Figures 6.161 through 6.164). Again, the SBM source had larger amounts of  $\text{CHCl}_3$ -extractable C than did the plots treated with the other N sources. This was consistent with the larger amounts of C found in the SBM relative to the  $\text{NH}_4\text{NO}_3$  and LCM (Table 2.4). There were no differences observed between N application rates (Table 6.11). There was little evidence that  $\text{CHCl}_3$ -extractable C levels were increasing between 1992 and 1993 which suggested that the microbial biomass had reached an equilibrium between manure C and N additions. Elevated biomass C and N levels have been correlated to N mineralization (Carter and MacLeod, 1987; Myrold, 1987). Therefore, it is possible that greater amounts of N were supplied to the crop from N mineralization in the SBM treatments, minimizing the accumulation of  $\text{NO}_3^-$  and  $\text{NO}_3^-$  loss. However, more sampling over a longer period should be implemented to investigate the dynamics of manures and the microbial population response.

Figure 6.153:  $\text{CHCl}_3$ -extractable N for the various N sources for the 0 - 15 cm depth.

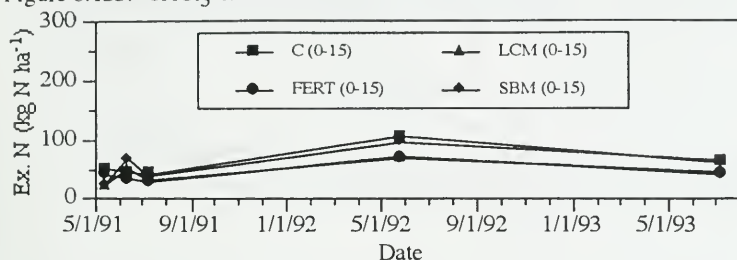


Figure 6.154:  $\text{CHCl}_3$ -extractable N for the various N sources for the 15 - 30 cm depth.

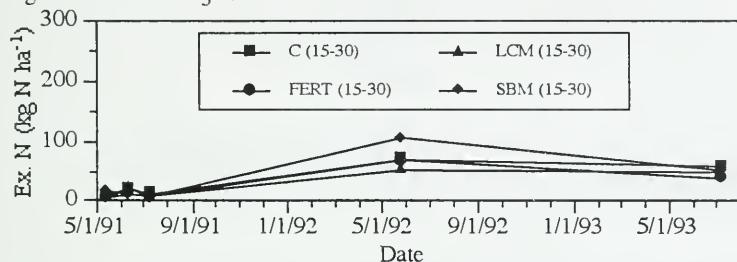


Figure 6.155:  $\text{CHCl}_3$ -extractable N for the various N sources for the 30 - 60 cm depth.

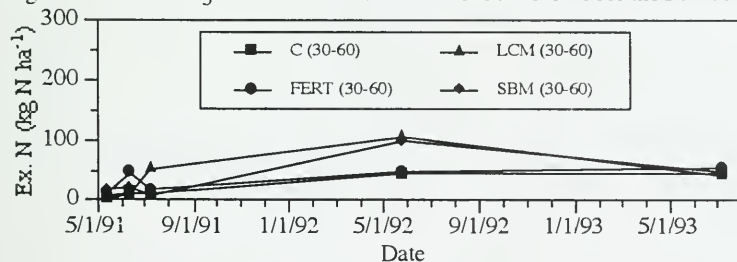


Figure 6.156:  $\text{CHCl}_3$ -extractable N for the various N sources for the 0 - 60 cm depth.

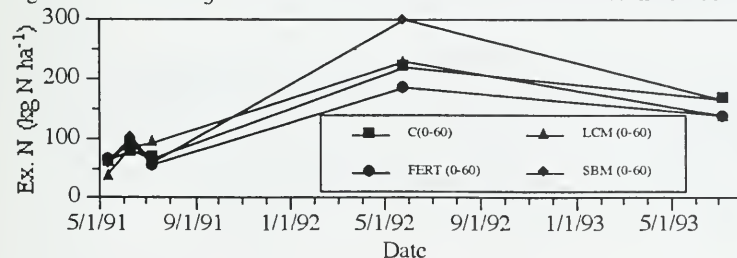


Figure 6.157:  $\text{CHCl}_3$ -extractable N for the various N rates for the 0 - 15 cm depth.

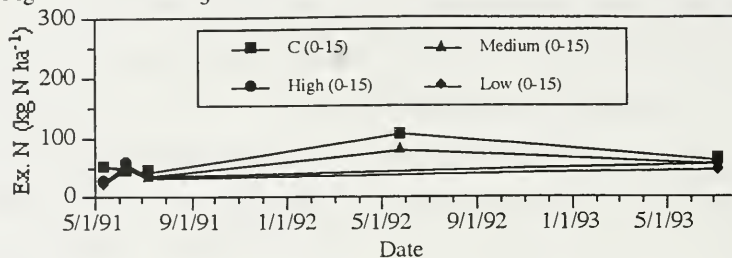


Figure 6.158:  $\text{CHCl}_3$ -extractable N for the various N rates for the 15 - 30 cm depth.

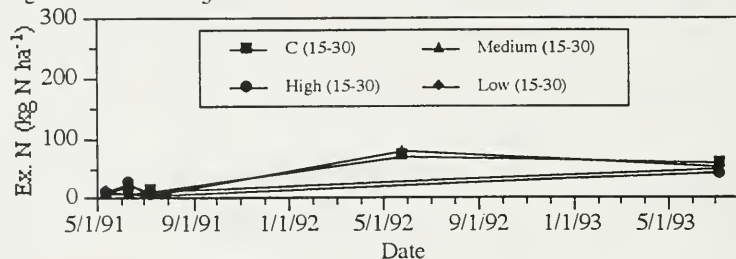


Figure 6.159:  $\text{CHCl}_3$ -extractable N for the various N rates for the 30 - 60 cm depth.

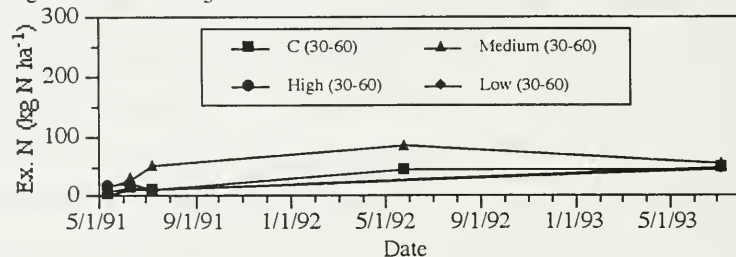


Figure 6.160:  $\text{CHCl}_3$ -extractable N for the various N rates for the 0 - 60 cm depth.

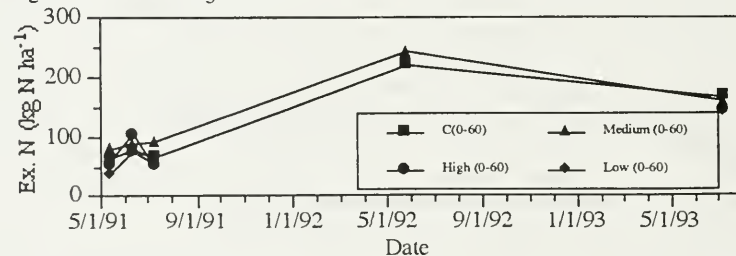


Figure 6.161:  $\text{CHCl}_3$ -extractable C for the various N sources for the 0 - 15 cm depth.

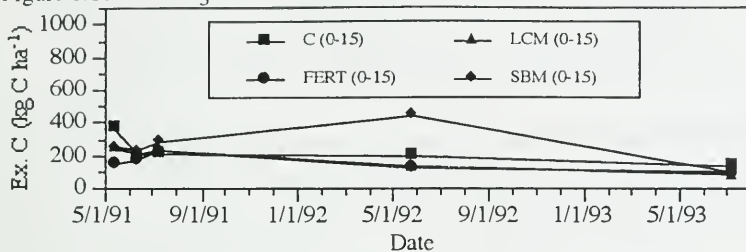


Figure 6.162:  $\text{CHCl}_3$ -extractable C for the various N sources for the 15 - 30 cm depth.

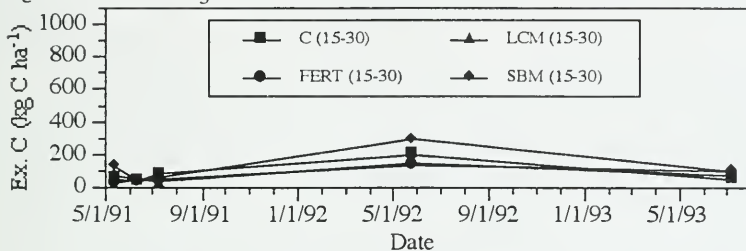


Figure 6.163:  $\text{CHCl}_3$ -extractable C for the various N sources for the 30 - 60 cm depth.

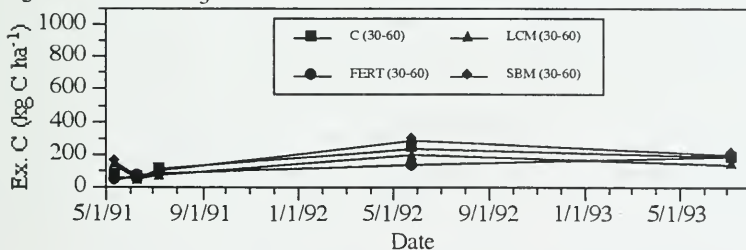


Figure 6.164:  $\text{CHCl}_3$ -extractable C for the various N sources for the 0 - 60 cm depth.

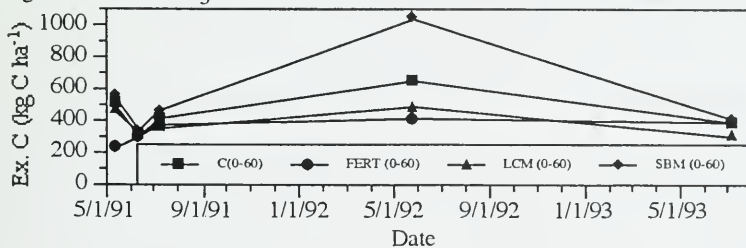


Figure 6.165:  $\text{CHCl}_3$ -extractable C for the various N rates for the 0 - 15 cm depth.

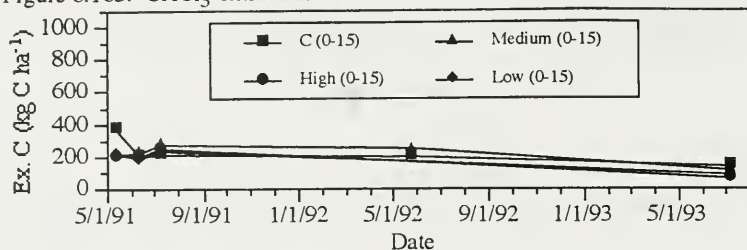


Figure 6.166:  $\text{CHCl}_3$ -extractable C for the various N rates for the 15 - 30 cm depth.

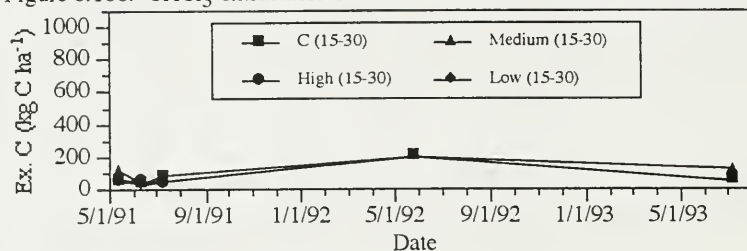


Figure 6.167:  $\text{CHCl}_3$ -extractable C for the various N rates for the 30 - 60 cm depth.

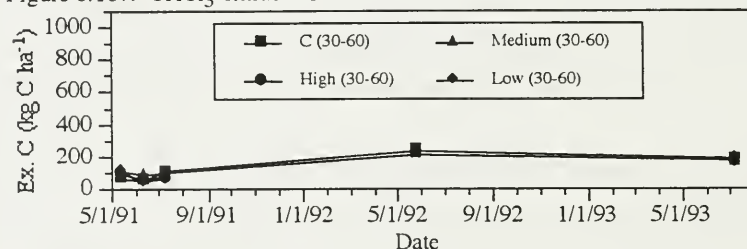
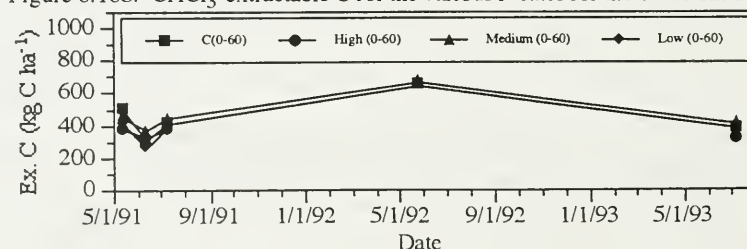


Figure 6.168:  $\text{CHCl}_3$ -extractable C for the various N rates for the 0 - 60 cm depth.





## 6.6 Summary

Amounts of soil mineral  $\text{NH}_4^+$  remained low throughout the length of the growing season except for the two to three weeks after N application of the  $\text{NH}_4\text{NO}_3$  and LCM sources. The SBM treated plots indicated little increase in mineral  $\text{NH}_4^+$  after N application. The rapid decline in amounts of  $\text{NH}_4^+$  in the soil profile was consistent with negligible amounts in the drainage water measured with the solution samplers. In addition, it is a direct result of the fairly rapid nitrification process that is occurring at this site and which has been commonly observed in other areas of southern Ontario.

Again, residual amounts of soil mineral  $\text{NO}_3^-$  after harvest followed the same trends as were observed with the solution sampler data. This indicated the importance of minimizing the amount of mineral N in the soil profile after harvest and before the leaching period begins. Soil  $\text{NO}_3^-$  was observed to decrease as a function of N source in the order of  $\text{NH}_4\text{NO}_3 > \text{LCM} > \text{SBM}$ , as a function of N application rate in the order of high > medium > low and in the order of spring > fall. These differences were most obvious in the  $\text{NH}_4\text{NO}_3$  source followed by the LCM source followed by the SBM source. It appeared that increased microbial processes in the manured soils was responsible for reducing the differences relative to the  $\text{NH}_4\text{NO}_3$  treated soils. For example, it will be shown in Chapter 7 that the amounts of denitrification in the SBM treated plots was far greater than the other two N source treated plots.

There was evidence that from the 0 - 60 cm depth, the SBM treated plots had greater  $\text{CHCl}_3$ -extractable N and C amounts than did the plots treated with the other N sources. This has been correlated to greater N mineralization (Carter and MacLeod, 1987; Myrold, 1987). Differences between N application rates were less obvious. Spring treated plots had greater values than fall treated plots. It was suggested that detailed research examining the microbial response to manure applications over longer periods of time be investigated. This would help to quantify the extent of increased leaching of N from manured soils once the microbial population has reached an equilibrium with annual additions of manure C and N.

# Chapter 7 Denitrification

## 7.1 Introduction

In the spring and summer of 1993, David Bergstrom and Mario Tenuta made various denitrification measurements to characterize the denitrification process at this site. David Bergstrom has summarized the results of these measurements and has presented them here. The various measurements that were made and their methodologies were described in section 2.4.5. In addition, a graduate student at the University of Guelph, Petra Loro, performed her M.Sc. research on denitrification at the same site (Loro, 1993).

There were three objectives of this denitrification study: (1) to measure the intensity and duration of denitrification and  $N_2O$  production from spring application of manure, and to identify the regulators of denitrification responsible for these features; (2) to measure relative amounts of denitrification for four specific treatments; and (3) to compare denitrifying enzyme activity (DEA) measurements for all treatments and at three soil depths.

## 7.2 Results

### 7.2.1 Temporal Patterns and Regulation of N Gas Production

Regulation of denitrification and  $N_2O$  production was examined by comparison of temporal patterns of measured soil parameters, and by Spearman rank correlation of mean values for each sampling date. The temporal pattern of denitrification and  $N_2O$  production was compared with that of soil water content, and extractable C and  $NO_3^-$ . These soil measurements were intended to assess the three proximate regulators of denitrification; aeration, substrate C supply and  $NO_3^-$  content (Tiedje, 1988). Because addition of solid beef manure affected the soil bulk density for that treatment, we assumed that soil water content would be a better indicator of aeration status than air-filled porosity for all four treatments.

On the control and fertilized plots, the temporal pattern of denitrification was very similar to that of soil water content (Figures 7.1 and 7.2). Likewise, mean denitrification rate was strongly

related to both soil water content and air-filled porosity on both treatments (Table 7.1). Rates of both denitrification and  $\text{N}_2\text{O}$  production, on the control and  $\text{NH}_4\text{NO}_3$  treated plots, were much lower than on the plots that received manure (Figures 7.2 and 7.3). Because the amount of denitrification for these two treatments was determined principally by changes in soil water content, it is very likely that it can be estimated by a model such as that of Li et al. (1992) based on rainfall. In their model, wetting of soil above a threshold value restricts aeration, and drying of soil recharges the soluble C pool. The extractable C measurements indicated some recharge of available C from drying of soil (Figure 7.5). The extractable C measurements assessed pool size rather than turnover, and were limited in this respect. The pattern of  $\text{N}_2\text{O}$  production did not closely follow that of denitrification on either the control or the fertilized plot (Figure 7.3). Moreover,  $\text{N}_2\text{O}$  production and denitrification were not correlated for these two treatments (Table 7.2). The initial peak of  $\text{N}_2\text{O}$  production on the control plot (May 17, 1993) occurred as the soil dried and  $\text{NO}_3^-$  content increased. It was not accompanied by an increase in denitrification rate. Hence, it most likely resulted from increased nitrification in the drying soil. On the fertilized plot, production of  $\text{N}_2\text{O}$  increased from June 7, 1992 onward, and was most likely a result of nitrification of fertilizer  $\text{NH}_4^+$ . The relationship between  $\text{N}_2\text{O}$  production and respiration rate for both treatments (Table 7.2) derived principally from increasing production of both  $\text{N}_2\text{O}$  and  $\text{CO}_2$  in the second half of the sampling period, which resulted from warming of soil. Production of  $\text{N}_2\text{O}$  by nitrifiers would be expected when denitrification rates are very low, as was the case on the control and fertilized plots, and is taken into account in the model of Li et al. (1992).

Application of both liquid cattle manure and solid beef manure resulted in more denitrification than for the control and fertilizer treatments (Figure 7.2). The two manure treatments, however, showed different regulation. For the LCM treatment, the temporal patterns of denitrification and the three proximate regulators were not very similar (Figures 7.1, 7.4 and 7.5).

Figure 7.1: Soil water content measured during the 1993 denitrification study.

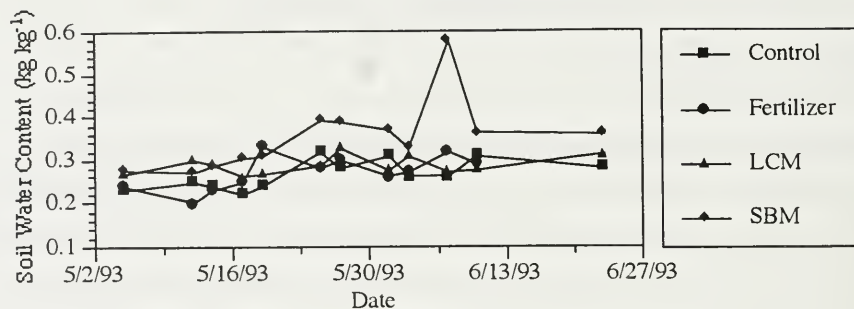


Figure 7.2: Denitrification rate during the 1993 denitrification study.

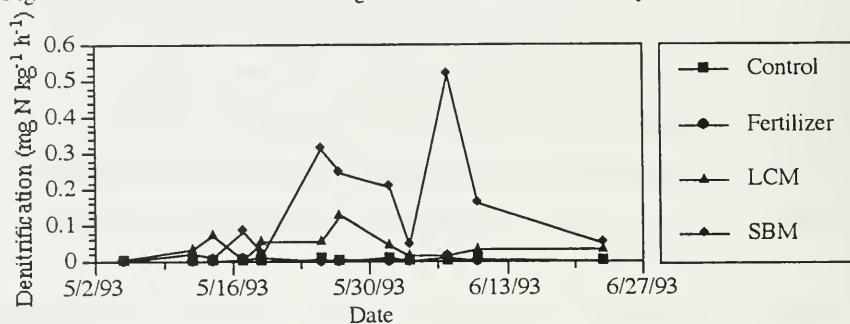


Figure 7.3:  $\text{N}_2\text{O}$  production during the 1993 denitrification study.

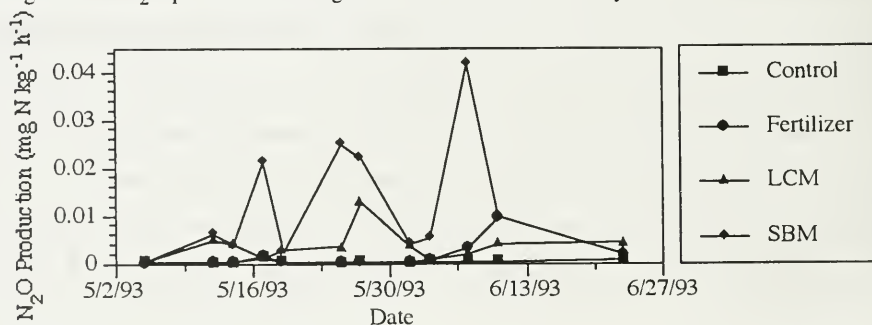


Table 7.1: Spearman rank correlation coefficients for denitrification rate with selected soil properties, for individual treatments and pooled data, using mean values for each sampling date.

Variable	Treatment <sup>+</sup>				
	Control	NH <sub>4</sub> NO <sub>3</sub>	LCM	SBM	Mean
	n = 12	n = 11	n = 13	n = 12	n = 48
Soil Water Content	0.75 <sup>**</sup>	0.72 <sup>*</sup>	0.40	0.91 <sup>***</sup>	0.77 <sup>***</sup>
Air-Filled Porosity	-0.80 <sup>**</sup>	-0.73 <sup>*</sup>	-0.24	-0.52	-0.38 <sup>*</sup>
Extractable C	0.26	-0.38	0.50	0.45	0.77 <sup>***</sup>
Nitrate Content	-0.13	0.15	0.37	0.13	0.15
Ammonium Content	-0.02	-0.03	0.66 <sup>*</sup>	0.08	0.30 <sup>*</sup>
Respiration Rate	0.15	0.01	0.12	0.41	0.73 <sup>***</sup>

<sup>+</sup> high rates of fertilizer, liquid cattle manure and solid beef manure, applied in spring.

<sup>\*</sup>, <sup>\*\*</sup>, <sup>\*\*\*</sup> significant at the 0.05, 0.01 and 0.001 probability level, respectively.

Table 7.2: Spearman rank correlation coefficients for N<sub>2</sub>O production with selected soil properties, for individual treatments and pooled data, using mean values for each sampling date.

Variable	Treatment <sup>+</sup>				
	Control	NH <sub>4</sub> NO <sub>3</sub>	LCM	SBM	Mean
	n = 12	n = 11	n = 13	n = 12	n = 48
Soil Water Content	-0.22	0.54	0.57 <sup>*</sup>	0.62 <sup>*</sup>	0.57 <sup>***</sup>
Air Filled Porosity	0.15	-0.40	-0.51	-0.15	-0.18
Extractable C	-0.12	0.14	0.47	0.68 <sup>*</sup>	0.80 <sup>***</sup>
Nitrate Content	0.36	0.46	0.33	0.29	0.37 <sup>**</sup>
Ammonium Content	0.15	0.25	0.53	0.38	0.48 <sup>***</sup>
Respiration Rate	0.64 <sup>*</sup>	0.65 <sup>*</sup>	0.19	0.38	0.83 <sup>***</sup>
Denitrification Rate	-0.26	0.39	0.74 <sup>**</sup>	0.83 <sup>***</sup>	0.79 <sup>***</sup>

<sup>+</sup> high rates of fertilizer, liquid cattle manure and solid beef manure, applied in spring.

<sup>\*</sup>, <sup>\*\*</sup>, <sup>\*\*\*</sup> significant at the 0.05, 0.01 and 0.001 probability level, respectively.

Figure 7.4:  $\text{NO}_3^-$  - N during the 1993 denitrification study.

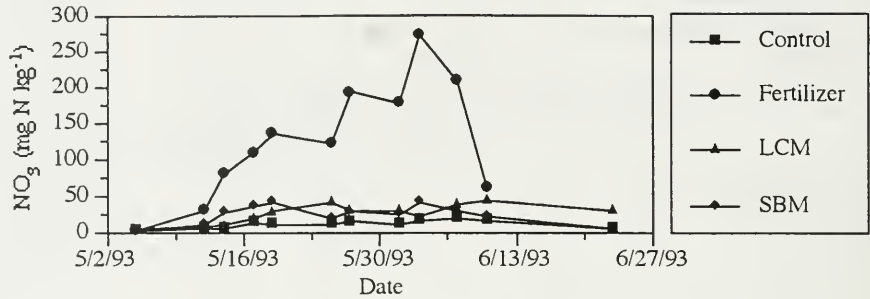


Figure 7.5: Extractable C during the 1993 denitrification study.

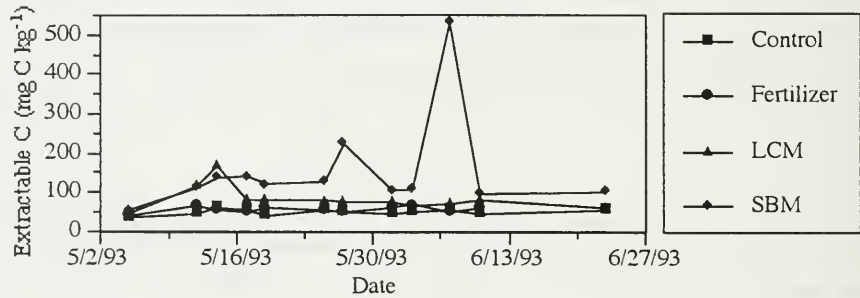
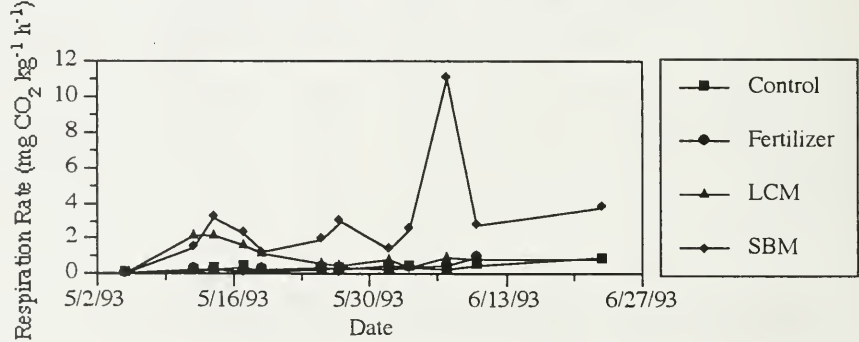


Figure 7.6: Respiration rate during the 1993 denitrification study.



Denitrification rate was only weakly related to  $\text{NH}_4^+$  content (Table 7.1). Carbon supply from LCM was at a maximum early in the sampling period and declined after May 12, 1993. Yet, the highest soil water content (lowest air-filled porosity) occurred after C supply began to decline, on May 25, 1993. Because both C supply and soil water content influence denitrification, neither variable alone explained the temporal pattern of denitrification. Soil water content was relatively high on two dates in the second half of the sampling period (June 1 and June 10, 1993), without a marked increase in denitrification. This observation pointed to depletion of substrate C, following the maximum measured denitrification rate on May 25, 1993 when soil water content was a maximum. Nitrous oxide production was strongly related to denitrification rate, and less strongly related to soil water content (Figures 7.1 and 7.3; Table 7.2).

For the SBM treatment, the temporal patterns of denitrification rate,  $\text{N}_2\text{O}$  production, soil water content and extractable C content were similar. Denitrification rate was very strongly related to soil water content (Table 7.1). Because the wettest soil cores had the highest extractable C contents for this treatment, soil water content probably affected both aeration and C supply. Such an interaction between C supply and soil water content may not be accounted for by the C subroutine in a model such as that of Li et al. (1992), which assumes a recharge of the soluble C pool during soil drying. The SBM contained a substantial amount of straw, and was not uniformly mixed into the soil. A few soil cores contained a large amount of manure, resulting in very high soil water contents ( $> 0.4 \text{ kg kg}^{-1}$ ) and high extractable C contents (Figures 7.7 through 7.9). These few cores had the highest denitrification rates. Two outliers were particularly noticeable, and influenced mean denitrification rates for their respective sampling dates. Because N gas production rates on each sampling date represented the mean value for 12 soil cores, the effect of the two outliers on the mean rate was limited. Furthermore, these outliers indicated the very high rates of N gas production at particular locations within the plots. High C supply in the wettest soil samples resulted in the high denitrification rates for this manure treatment. Nitrous oxide production was very strongly related to denitrification rate, and less strongly to soil water content (Table 7.2).



Figure 7.7: Denitrification rate versus soil water content for the SBM-High-Spring treated plots.

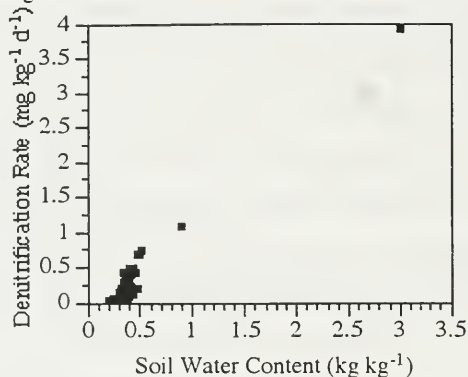


Figure 7.8: Denitrification rate versus soil water content for the SBM-High-Spring treated plots without outliers.

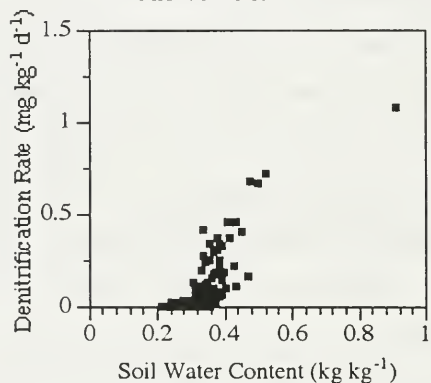
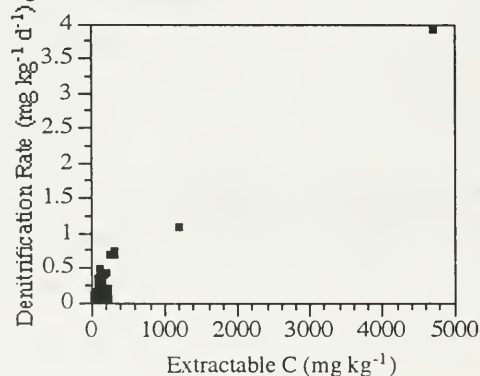


Figure 7.9: Denitrification rate versus extractable C for the SBM-High-Spring treated plots.





### 7.2.2 Relative Amounts of N Gas Production Among Treatments

The relative amounts of N gas production for the four treatments was determined principally by C supply. Application of SBM resulted in much higher rates of denitrification and  $\text{N}_2\text{O}$  production than occurred with the other three treatments (Figures 7.2 and 7.3). The supply of C from SBM (as indicated by respiration rate and extractable-C content) was also greater than for the other treatments (Figure 7.5 and 7.6). The larger supply of C from SBM also resulted in a longer duration of elevated rates of N gas production than with the LCM. Soil water content also influenced the relative amounts of N gas production. The SBM treatment had very high gravimetric soil water contents when C supply was also very high. When data from all four treatments were considered together, denitrification rate was strongly related to soil water content, extractable C content and respiration rate (Table 7.1). Nitrous oxide production was more strongly related to C supply (extractable C content and respiration rate) than to soil water content (Table 7.2).

Amounts of denitrification and  $\text{N}_2\text{O}$  production during the sampling period (49 d) were estimated by integration of the areas under the curves (Figures 7.2 and 7.3). Total respiration was also estimated in this manner. Estimates of  $\text{N}_2\text{O}$  flux based on production from soil cores are less exact than continuous measurements of  $\text{N}_2\text{O}$  flux in the field. On the other hand, estimates of denitrification from soil core measurements with acetylene blockage have been shown to be comparable to estimates obtained using  $^{15}\text{N}$  (Parkin et al., 1985). Although N gas production was extremely variable within the plots, replication ( $n = 12$ ) was sufficient to identify treatment effects. Because the frequency distribution of individual measurements is less skewed for higher rates of gas production (Bergstrom and Beauchamp, 1993), mean values for higher rates should be less affected by spatial variability. Integration of the area under the curves will overestimate N gas production during intervals between sampling dates when rainfall is infrequent. For this reason, we compared the temporal patterns of denitrification rate, soil soil water content and precipitation for the SBM (Figure 7.10), and concluded that rain fell frequently enough to limit such overestimation of N gas production.

The denitrification rates were measured overnight in the laboratory at 25 °C, which was considerably warmer than temperatures in the field. Therefore, we adjusted each measured denitrification rate to account for the difference between field and laboratory temperatures on the sampling date, using a curvilinear relationship determined experimentally by Dorland and Beauchamp (1991). We used daily temperature recorded near the experimental site at 800 h at the 5 cm depth under sod. While these temperatures were not exactly the same as those of tilled soil at the experimental site, they provided a reasonable estimate of day to day changes. The relationship described by Dorland and Beauchamp (1991) was selected because it was obtained with soil collected near the experimental site that had been amended with glucose. We considered it applicable to the manure treatments. Because the N<sub>2</sub>O and CO<sub>2</sub> production were measured within approximately 3 h of collection of soil cores, rates were not adjusted for differences in temperature between the field and the laboratory.

Estimates of N gas production on the control and fertilized plots (Table 7.3) were fairly low ( $< 5 \text{ kg N ha}^{-1}$ ), and comparable to measurements of other workers (Nieder et al. 1989). Nitrous oxide production on the fertilized plots was of the same order as denitrification, in contrast to the other treatments. The relatively large amount of N<sub>2</sub>O on the fertilized plots most likely derived from nitrification of fertilizer NH<sub>4</sub><sup>+</sup>. A strict comparison of N<sub>2</sub>O production and denitrification is limited by the temperature adjustment of the denitrification rates. Both denitrification and N<sub>2</sub>O production on the manured plots were larger than expected, especially for application of SBM (Table 7.3). Given the limitations of soil core measurements in estimation of gas production in the field, it is possible that rates were overestimated. Yet, the same methods were employed for all four treatments, and gave reasonable results for the control and fertilized plots. Consequently, at the very least, the results indicated increased denitrification for the manure treatments; especially in the case of solid beef manure. The ratios of N<sub>2</sub>O:N<sub>2</sub> for the manure treatments were larger than those reported in similar studies (Rolston et al., 1978), and as such are inconsistent with an overestimate of denitrification.

Figure 7.10: Relationship between soil water content, denitrification rate and precipitation for the SBM treated plots.

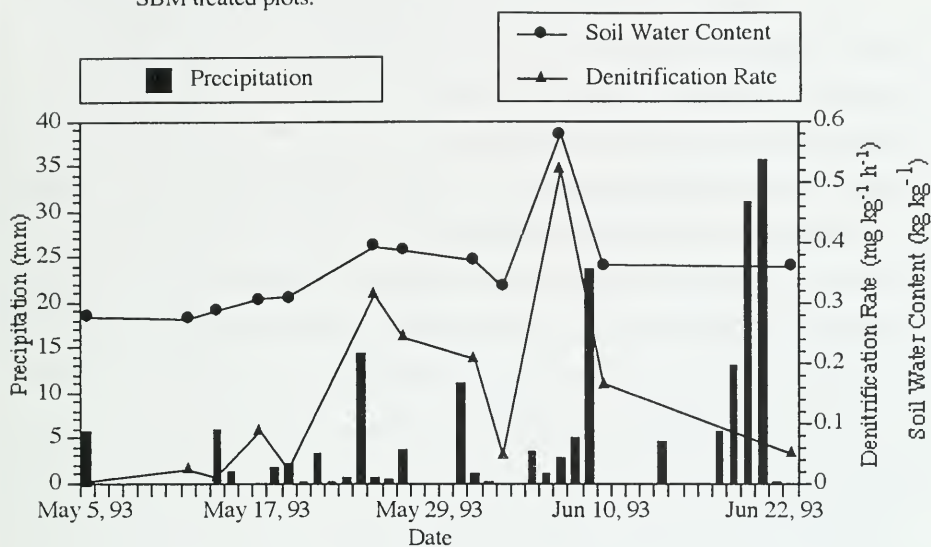


Table 7.3. Total denitrification, N<sub>2</sub>O production and respiration over the sampling period (49 d)<sup>+</sup>.

Treatment	Denitrification*	N <sub>2</sub> O production	Respiration
	(kg N ha <sup>-1</sup> )		(kg C ha <sup>-1</sup> )
Control	2.31	0.56	885
Fertilizer	3.23	4.81	956
LCM	29.5	8.09	2233
SBM	115	26.5	6774

<sup>+</sup> assuming depth = 15 cm and bulk density = 1.33 Mg m<sup>-3</sup>.

\* adjusted for temperature as described in text.

The large amount of denitrification estimated for the manure treatments, however inexact, deserves attention. Several earlier studies provided evidence for large amounts of denitrification in soil receiving large applications of manure. Wallingford et al. (1975) examined effects of yearly applications of very high rates of beef feedlot manure on denitrification in an irrigated silty clay loam. In N balance calculations, unaccounted for N ranged from 700 to 2830 kg ha<sup>-1</sup>. Some of this N may have been lost by leaching. While lowered O<sub>2</sub> and increased N<sub>2</sub>O and CH<sub>4</sub> concentrations in soil atmosphere, and increased solution concentrations of Fe and Mn provided indirect evidence for denitrification and reducing conditions, methods for quantifying denitrification in the field were not then available. Guenzi et al (1978) measured losses of N in a greenhouse experiment in which dry cattle manure was mixed into soil at rates equivalent to 45 and 90 t ha<sup>-1</sup>, together with either K<sup>15</sup>NO<sub>3</sub> or (<sup>15</sup>NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Soil was watered daily to field capacity. Recovery of labelled and total N from pots after 39 d indicated denitrification losses as high as 1760 kg ha<sup>-1</sup>. Moreover, presence of <sup>15</sup>N-enriched N<sub>2</sub> for the (<sup>15</sup>NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> treatment indicated that both nitrification and denitrification occurred. Rolston et al. (1978) estimated absolute amounts of denitrification in the field on small plots to which manure (34 t ha<sup>-1</sup>) was applied. Fertilizer (<sup>15</sup>N-enriched KNO<sub>3</sub>) was applied at a rate of 300 kg N ha<sup>-1</sup>, and gas flux was determined by measurement of N<sub>2</sub>O and <sup>15</sup>N<sub>2</sub> accumulated under soil covers. Nitrous oxide above ambient was assumed to be derived from fertilizer N. At water contents maintained very close to saturation and a soil temperature of 23 °C, 218 kg N ha<sup>-1</sup> was denitrified. Less denitrification occurred at lower water contents, and a lower temperature. Rice et al. (1988) measured substantial amounts of denitrification in soil injected with fermentation wastes. Denitrification was measured using soil cores collected from the field site, and acetylene blockage. Estimates of total denitrification were 440 and 270 kg N ha<sup>-1</sup> for the two wastes. Because there was little NO<sub>3</sub><sup>-</sup> initially present in the soil, and none in the waste, substantial nitrification must have occurred. Such rapid nitrification may be necessary for large amounts of denitrification from manure application.

### 7.2.3 Denitrifying Enzyme Activity (DEA) and Implications for $\text{NO}_3^-$ Leaching

Denitrifying enzyme activity (DEA) measurements were made on soil samples collected from all plots on May 14, 1993 to provide a relative comparison of denitrifying activity among treatments, and with depth. Denitrifying enzyme activity is a measurement of reaction rate under optimal conditions. As such, it provides an indirect measurement of the relative concentration of active denitrifying enzymes present in the sample at the time of collection. For all treatments, DEA decreased appreciably with depth, to almost nil values at the 30-60 cm depth (Figure 7.11). The figure presents mean DEA of the four treatments for which gas production was measured, and a mean value for all treatments. The appreciable decrease in DEA with depth in the present study supports the earlier finding of P. Loro at the same site (personal communication), and is similar to most but not all results of other studies. Groffman et al. (1992) measured soil microbial properties to describe nitrate dynamics in catenas of three riparian forests. Denitrifying enzyme activity decreased sharply with depth. Both DEA and microbial biomass were consistently low or nil at and below the seasonal high water table. Yeomans et al. (1992) measured denitrification capacity and potential of subsurface agricultural soils. While denitrifying bacteria were present at all depths (0-300 cm), the rate of denitrification in subsoils was limited by availability of organic C. Likewise, carbon limitation of denitrification has been reported for aquifer sediments (Bradley et al., 1992). Weier and MacRae (1992) observed a decline in most probable number counts of denitrifiers with depth under two crops. Denitrifying bacteria were, however, present at the 110-115 cm depth. The population seemed to be controlled by soil water content. Finally, Parkin and Meisinger (1992) measured soil properties affecting denitrification to a depth of 400 cm beneath conventionally tilled and no tillage corn plots. Organic C content, total viable bacteria and numbers of denitrifiers decreased exponentially with depth. No DEA and  $\text{CO}_2$  production were measured below the 180 cm depth. There was a marked change in texture from the 120 to 180 cm depth, with sand content increasing to 90 %. The change in texture in the profile may have affected some measurements. Parkin and Meisinger (1992) concluded that lack of C below the rooting zone limited denitrification

and the microbial population. Furthermore, surface tillage practices did not influence microbial activity below the rooting zone, via transport of soluble C.

We also compared DEA in the 0 - 15 cm depth for all treatments (Figure 7.12). Variability of DEA in samples was considerable. Because DEA was not markedly larger in plots that received fall application of fertilizer and manure compared to the control plot, the increase in denitrifying activity from amendments did not seem persistent. Only the high rates of manure application in spring produced markedly larger DEA. For DEA of the 0-15 cm layer of the control plots, and plots receiving high rates of fertilizer, liquid cattle manure and solid beef manure in spring, we used orthogonal contrasts to test for particular treatment comparisons. While all three amendments affected DEA, application of manure produced much larger DEA than application of fertilizer. This observation is consistent with a predominance of C over  $\text{NO}_3^-$  in regulation of denitrification in this soil.

The decrease in DEA with depth indicated that appreciable rates of denitrification were not likely at depth in the profile. Furthermore, the treatment comparisons indicated that very large increases in denitrification will occur following high rates of manure application.

### 7.3 Summary

Three results of this study can be emphasized. Firstly, manure application increased denitrification more than fertilizer application, because of added substrate C. Higher rates of denitrification and  $\text{N}_2\text{O}$  production occurred for a longer duration on the plots which received solid beef manure, compared to liquid cattle manure. Secondly, fertilizer application increased  $\text{N}_2\text{O}$  production substantially compared to the control treatment. Thirdly, the decrease in DEA with depth indicated that appreciable rates of denitrification did not occur at depth. This conclusion is, however, tentative.



Figure 7.11: Denitrifying enzyme activity versus depth for the SBM plots.

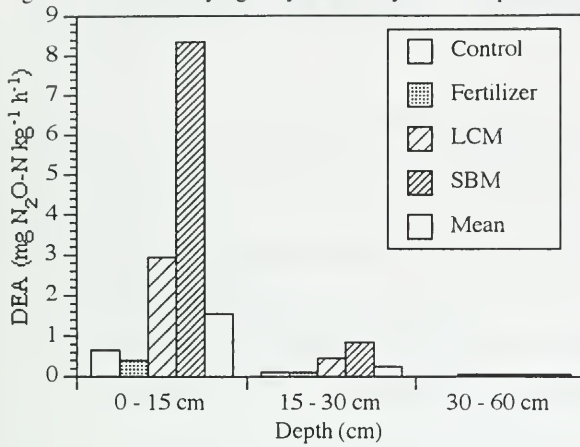
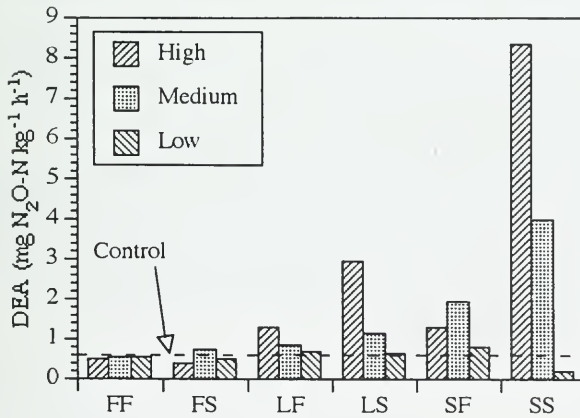


Figure 7.12: Mean DEA for the 0 - 15 cm depth of all treatments<sup>+</sup> receiving high N application rates.



<sup>+</sup> First letter is the N source; second is the application time.  
ie. Fertilizer Spring - FS; SBM Fall - SF.

## Chapter 8 Summary and Future Research

### 8.1 Summary

In the last thirty years, manure has gone from being regarded as a fertilizer to a pollutant and back to a fertilizer. The advantages of using manure as a fertilizer, relative to inorganic fertilizer, include soil conditioning which, by increasing the soil organic matter, can reduce wind and water erosion. Larger livestock operations on smaller landbases produce larger amounts of manures which may result in excessive manure applications if disposal occurs on site. Excessive rates of manure application have been shown to increase the potential for contamination of groundwater by  $\text{NO}_3^-$ . However, this report and others have suggested that sub-excessive rates of manure application, relative to inorganic fertilizers, can reduce the potential for  $\text{NO}_3^-$  contamination of groundwater and still produce acceptable crop yields. Concern for manure disposal is centered not only around  $\text{NO}_3^-$  - N contamination of groundwater but also around bacterial contamination (faecal coliform) of groundwater. It should be stressed that this report did not address the bacterial contamination problem or the chance that manures may mineralize large amounts of N once a new equilibrium has been reached between manure applications and soil organic matter.

In addition, this report indicated that increased denitrification losses in the form of  $\text{N}_2\text{O}$  and NO occur from manured soils relative to synthetically fertilized soils. These gases are known to be damaging to the earth's protective ozone layer and they are also known to contribute to the warming of the earth's atmosphere through the greenhouse effect.

### 8.2 Future Research

The future of manure research appears to be centering around a "systems" approach where integrated management systems (from animal intake to soil incorporation) are being evaluated in terms of such things as animal nutrition, plant nutrient requirements and environmental impacts. One of the recommendations of a 1991 manure report was to implement long term research plots for the study of continuous land applications of manures (Paul et al., 1991). This would assist in



understanding how long it takes for equilibrium to be reached between the soil organic matter and continuous manure applications. This would quantify the amount of mineralization of organic N that might occur some years after manure applications have been started. A recent literature review prepared for Agriculture Canada (Goss et al., 1993) identified six high priority areas that require additional research:

1. Nutrient composition in manure.
2. Gaseous losses.
3. Application methods.
4. Nutrient management and accounting.
5. Assessment of off-farm costs.
6. Manure management systems research.

Several solutions to the manure disposal problem are being implemented in different countries. The European Community has set a limit of  $170 \text{ kg} - \text{N ha}^{-1} \text{ year}^{-1}$  to land that is susceptible to  $\text{NO}_3^-$  leaching. The Netherlands have begun to solve their 80 million tonnes  $\text{year}^{-1}$  manure disposal problem by processing some of the waste into fertilizer pellets which can be used locally or exported. Farmers prefer the pellets to inorganic fertilizers because of the organic content. In addition to limiting manure application rates, changes in breeding and feeding practices are also being investigated with regards to reducing amounts of N in manure. Table 8.1 gives a list of feed related measures which can be quickly implemented with minimal investment (FEFANA, 1992). Note that the potential reductions in N output are not necessarily cumulative and that these measures and reduction values are estimates for animal operations in general.

Table 8.1: Feed related measures and potential N reduction in animal excreta.

Measure	Examples	Potential Reduction (%)
Feed Supplements	Use of enzymes, growth promoters	30 - 35
Feed Systems	Phase feeding, better formulations	25 - 30
Animals	Breeding and selection for N retention	na *
N in Manure	Better conversion using all influences	na
Manure Processing	Improved handling and use of manure on land	na

\* na - not available

With respect to gaseous losses of N ( $N_2O$ , NO), the Agroclimatology group in the Department of Land Resource Science, University of Guelph is continuing their research of these losses using a laser. The laser is fully automated and continues to monitor the losses of  $N_2O$  and NO from a manured field at the Elora Research Station. This experiment will provide information with regards to denitrification losses following manure applications as well as denitrification "episodes" following precipitation events. Current methods for measuring denitrification losses are, in most cases, non-continuous as well as both labour and cost intensive.

The above discussion would appear to indicate that significant reductions in manure N from more efficient feed systems are possible. Further research and increased mechanization of the feeding systems will help to quantify and bring about these reductions. In addition, increased research into the relationships between manure application, soil type, climate and crop type - manure use efficiency is required to set regulations regarding manure N content and the environmentally safe manure application rate. Finally, there is still a need for a proactive approach and innovative ideas to produce new solutions to manure disposal.

## Chapter 9 References

- Addiscott, T.M. and D.S. Powlson. 1992. Partitioning losses of nitrogen fertilizer between leaching and denitrification. *J. Agric. Sci.* 118: 101-107.
- Addiscott, T.M., A.P. Whitmore and D.S. Powlson. 1991. Farming, Fertilizers and the Nitrate Problem. C.A.B. International, Wallingford, UK. pp. 170.
- Adriano, D.C., A.C. Chang and R. Sharpless. 1974. Nitrogen loss from manure as influenced by moisture and temperature. *J. Environ. Qual.* 3:258-261.
- Azam, F., R. Mulvaney, F. Stevenson. 1988. Determination of in situ  $k_N$  by the chloroform fumigation-incubation method and mineralization of biomass N under anaerobic conditions. *Plant and Soil* 111: 87-93.
- Beauchamp, E.G. and D.W. Bergstrom. 1993. Denitrification. Pp 351-357 *In* M.R. Carter [Ed.]. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, Fl.
- Beauchamp, E.G. 1983. Response of corn to nitrogen in preplant and sideress applications of liquid dairy cattle manure. *Can. J. Soil Sci.* 63:377-386.
- Beauchamp, E.G. 1982. Ammonia volatilization from liquid dairy cattle manure in the field. *Can. J. Soil Sci.* 62:11-19.
- Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. *J. Hydrol.* 63:271-286.
- Bolton, H. Jr., L. Elliott, R. Papendick, D. Bezdicsek. 1985. Soil microbial biomass and selected soil enzyme activities: Effect of fertilization and cropping practices. *Soil Biol. Biochem.* 17:297-302.
- Bond, J.J., and W.D. Willis. 1969. Soil water evaporation: surface residue rate and placement effects. *Soil Sci. Soc. Am.J.* 33: 445-448.
- Bonde, T., J. Schnürer, T. Rosswall. 1988. Microbial biomass as a fraction of potentially mineralizable nitrogen in soils from long-term field experiments. *Soil Biol. Biochem.* 20:447-452.
- Bouldin, D.R., S.D. Klausner and W.S. Reid. 1984. Use of nitrogen from manure. *In* R.D. Hauck [Ed.]. Nitrogen in Crop Production, 1984. Am. Soc. Agron. Madison, WI.
- Bradley, P.M., M.Jr. Fernandez and F.H. Chapelle. 1992. Carbon limitation of denitrification rates in an anaerobic groundwater system. *Environ. Sci. Technol.* 26: 2377-2381.
- Bremer, E. and C. van Kessel. 1990. Extractability of microbial  $^{14}\text{C}$  and  $^{15}\text{N}$  following addition of variable rates of labelled glucose and  $(\text{NH}_4)_2\text{SO}_4$  to soil *Soil Biol. Biochem.* 22: 707-713.
- Brown, D.M., G.A. McKay and L.J. Chapman. 1968. The Climate of Southern Ontario. Climatological Studies No. 5. Meteorological Branch, Department of Transport. Toronto, Ontario.

- Burton, D.L., M.F. Younie, E.G. Beauchamp, R.G. Kachanoski, D.M. Brown and D.E. Elrick. 1993. Alternate crop management practices and nitrate contamination of groundwater with sandy soils used for tobacco production. Final Report. Dept. of Land Resource Science, Univ. of Guelph. Guelph, ON.
- Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Sci.* 117:311-314.
- Canadian Society of Soil Science. 1981. Manual on Soil Sampling and Methods of Analysis. J.A. McKeague, [Ed.]. Subcommittee on Methods of Analysis.
- Carter, M. 1986. Microbial biomass as an index for tillage-induced changes in soil biological properties. *Soil and Tillage Research.* 7:29-40.
- Carter, M. and J. MacLeod. 1987. Biological properties of some Prince Edward Island soils: Relationship between microbial biomass nitrogen and mineralizable nitrogen. *Can. J. Soil Sci.* 67:333-340.
- Cates, Jr., R.L. and D.R. Keeney. 1987. Nitrous oxide production throughout the year from fertilized and manured maize fields. *J. Environ. Qual.* 1: 443-447.
- Christensen, S. 1983. Nitrous oxide emission from a soil under permanent grass: Seasonal and diurnal fluctuations as influenced by manuring and fertilization. *Soil Biol. Biochem.* 15: 531-536.
- Comfort, S.D., K.A. Kelling, D.R. Keeney and J.C. Converse. 1988. The fate of nitrogen from injected liquid manure in a silt loam soil. *J. Environ. Qual.* 17:317-322.
- Coote, D.R. 1975. Runoff characteristics from feedlots and manure storage areas in south western Ontario. Engineering Research Service, Research Branch, Agriculture Canada.
- Coulson, A. 1967. Estimating runoff in southern Ontario. *Techn. Bull. No. 7. Inland Waters Branch, Dept. of Energy, Mines and Resources.*
- Dalal, R., R. Mayer. 1987. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern queensland. VII Dynamics of nitrogen mineralization potentials and microbial biomass. *Aust. J. Soil Res.* 25: 461-72:.
- Doran, J.W., and M.S. Smith. 1987. Organic matter management and utilization of soil fertilizer nutrients. pp. 53-72. In Mortvedt and Buxton (ed.) *Soil Fertility and Organic Matter as Critical Components of Production Systems.* Soil Science Society of America, Special Publication No. 19, Madison, Wisconsin. 166 pp.
- Doran, J.W. and J.F. Power. 1983. The effects of tillage on the nitrogen cycle in corn and wheat production. *In* R. Lowrance, A.R. Bertrand, F.B. Golley and P. Neubould [Eds.]. *Nutrient Cycling in Agricultural Ecosystems.* University of Georgia, College of Agriculture. Special Publications No. 23., Athens, Georgia.
- Dorland, S. and E.G. Beauchamp. 1991. Denitrification and ammonification at low soil temperatures. *Can. J. Soil Sci.* 71: 293-303.
- Elliott, E.T. 1986. Aggregate structure and carbon, nitrogen and phosphorous in native and cultivated soils. *Soil Sci. Soc. Am. J.* 50: 627-633.

- Edwards, W.M., Shipitalo, M.J., Owens, L.B. and Norton, L.D. 1989. Water and nitrate movement in earthworm burrows within long-term no-till cornfields. *J. of Soil and Water Conservation* 44: 240-243.
- Environment Canada. 1987. Canada Water Quality Guidelines. Supply and Services Canada. Hull, Quebec.
- Feddes, R.A., P.J. Kowalik and H. Zaradny. 1978. Simulation of Field Water Use and Crop Yield. Centre for Agricultural Publishing and Documentation, Wageningen, the Netherlands. John Wiley & Sons, Inc., New York.
- FEFANA. 1992. Improvement of the environment: possibilities for the reduction of nitrogen and phosphorous pollution caused by animal production. FEFANA office. rue Defacqz 1, Box 14, B-1050 Brussels, Belgium.
- Fletcher, D.A. 1991. A national perspective. *In* R.F. Follet, D.R. Keeney and R.M. Cruse. [Eds.]. Managing Nitrogen for Groundwater Quality and Profitability. Soil Science Society of America. Madison, WI. pp. 1-7.
- Focht, D.D. 1974. The effect of temperature, pH and aeration on the production of nitrous oxide and gaseous nitrogen - a zero order kinetic model. *Soil Sci.* 118: 173-179.
- Goss, M.J., J.R. Ogilvie, E.G. Beauchamp, D.P. Stonehouse, M.H. Miller and K. Parris. 1993. Current State of the Art on Manure/Nutrient Management. Final Report to Agriculture Canada. University of Guelph, Guelph, ON.
- Goss, M., D. Barry and D. Goorahoo. 1991. Sources and processes associated with nutrient contamination of water resources. *In* M.H. Miller, J.E. FitzGibbon, G.C. Fox, R.H. Gillham and H.R. Whitely. [Eds.]. Agriculture and Water Quality, Proceedings of an interdisciplinary symposium. Centre for Soil and Water conservation, Guelph ON. 1991.
- Groffman, P.M., A.J. Gold and R.C. Simmons. 1992. Nitrate dynamics in riparian forests: Microbial studies. *J. Environ. Qual.* 21: 666-671.
- Guenzi, W.D., W.E. Beard, F.S. Watanabe, S.R. Olsen and K.L. Porter. 1978. Nitrification and denitrification in cattle manure amended soil. *J. Environ. Qual.* 7: 196-202.
- Hoff, J.D., D.W. Nelson and A.L. Sutton. 1981. Ammonia volatilization from liquid swine manure applied to cropland. *J. Environ. Qual.* 10:90-95.
- Hoffman, D.W. and B.C. Matthews. 1963. Soil Survey of Wellington County, Ontario. Report No. 35 of the Ontario Soil Survey. Research Branch, Canada Department of Agriculture and Ontario Agricultural College, Guelph, ON.
- Jenkinson, D., D. Powlson. 1976. The effects of biocidal treatments on metabolism in soil. V. A method for measuring soil biomass. *Soil Biol. Biochem.* 8: 209-213.
- Kachanoski, R.G. and E.G. Beauchamp. 1991. Nitrogen Soil Test for Corn. Dept. of Land Resource Science, University of Guelph.
- Keeney, D.R. and R.F. Follet. 1991. Managing nitrogen for groundwater quality and farm profitability: Overview and introduction. *In* R.F. Follet, D.R. Keeney and R.M. Cruse. [Eds.]. Managing Nitrogen for Groundwater Quality and Profitability. Soil Science Society of America. Madison, WI. pp. 1-7.



- Kitur, B.K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of  $^{15}\text{N}$ -depleted ammonium nitrate applied to no-tillage and conventional tillage corn. *Agron. J.* 76: 240-242.
- Lee, D.M. 1984. A comparison of methods for measuring the saturated hydraulic conductivity of four field soils having a range of textures. M.Sc. thesis. University of Guelph, Guelph, ON.
- Li, C., S. Frohling and T.A. Frohling. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *J. Geophys. Res.* 97: 9759-9776.
- Linn, D.M. and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* 48:1267-1272.
- Loro, P. 1993. Denitrification at the Elora Research Station. M.Sc. Thesis. University of Guelph, Guelph, ON.
- Lowrance, R. 1992. Nitrogen outputs from a field-size agricultural watershed. *J. Environ. Qual.* 21: 602-607.
- Meisinger, J. J., V. A. Bandel, G. Stanford and J. O. Legg. 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage. I. Four - year results using labeled N fertilizer on an Atlantic Coastal Plain soil. *Agron. J.* 77:602-611.
- Mengel, D.B., D.W. Nelson and D.M. Huber. 1982. Placement of nitrogen fertilizers for no-till and conventional tillage corn. *Agron. J.* 74:515-518.
- Myrold, D. 1987. Relationship between microbial biomass nitrogen and a nitrogen availability index. *Soil Sci. Soc. Am. J.* 51:1047-1049.
- Nieder, R., G. Schollmayer and J. Richter. 1989. Denitrification in the rooting zone of cropped soils with regard to methodology and climate: A review. *Biol. Fertil. Soils.* 8: 219-226.
- Parkin, T.B. and J.J. Meisinger. 1989. Denitrification below the crop rooting zone as influenced by surface tillage. *J. Environ. Qual.* 18:12-16.
- Parkin, T.B., A.J. Sexstone and J.M. Tiedje. 1985. Comparison of field denitrification rates determined by acetylene-based soil core and nitrogen-15 methods. *Soil Sci. Am. J.* 49:94-99.
- Paul, J.W. 1991. Corn yields and potential for nitrate leaching from manures and inorganic N fertilizer. Ph.D Thesis. University of Guelph, Guelph, ON.
- Paul, J.W., E.G. Beauchamp, H.G. Whiteley and J. Sakarumpwanya. 1991. Fate of manure nitrogen at the Arkell and Elora research stations 1988-1990. Ontario Ministry of Agriculture and Food Special Research Contract No. SR8710-SW001.
- Power, J.F., J.W. Doran, and W.W. Wilhelm. 1986. Uptake of nitrogen from soil, fertilizer, and crop residues by no-till corn and soybean. *Soil Sci. Soc. Am. J.* 50: 137-142.
- Pratt, P.F., F.E. Broadbent and J.P. Martin. 1973. Using organic wastes as nitrogen fertilizer. *Calif. Agric.* 27(6):10-13.

- Present, E.W. and R.E. Wicklund. 1971. The Soils of Waterloo County. Report No. 44 of the Ontario Soil Survey. Research Branch, Canada Department of Agriculture; Dept. of Soil Science, University of Guelph, Guelph, ON; Ontario Dept. of Agriculture and Food.
- Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review*. 100:81-92.
- Rice, C.W., P.E. Sierzeza, J.M. Tiedje and L.W. Jacobs. 1988. Stimulated denitrification in the microenvironment of a biodegradable organic waste injected into the soil. *Soil Sci. Soc. Am. J.* 52: 102-108.
- Rice, C.W. and M.S. Smith. 1984. Short term immobilization of fertilizer nitrogen at the surface of no-till and plowed soils. *Soil Sci. Soc. Am. J.* 48:295-297.
- Risch, H.A., Jain, M. and Choi, N.W. 1985. Dietary factors and the incidence of cancer of the stomach. *Am. J. Epidemiology* 122, 947-959.
- Robertson, K., J. Schnurer, M. Clarholm, T. Bonde, T. Rosswall. 1988. Microbial biomass in relation to C and N mineralization during laboratory incubations. *Soil Biol. Biochem.* 20:281-286.
- Rolston, D.E., D.L. Hoffman and D.W. Toy. 1978. Field measurement of denitrification: I. Flux of  $N_2$  and  $N_2O$ . *Soil Sci. Soc. Am. J.* 42:863-869.
- Schipper, L.A., A.B. Cooper, C.G. Harfoot and W.J. Dyck. 1993. Regulators of denitrification in an organic riparian soil. *Soil Biol. Biochem.* 25: 925-933.
- Science Council of Canada. 1988. Water 2020: Sustainable Use for Water in the 21st Century. Science Council of Canada Report 40. Supply and Services Canada.
- Shuval, H.I and N. Gruener. 1977. Infant methemoglobinemia and other health effects of nitrates in drinking water. *Prog. Wat. Tech.* 8:183-193.
- Sing, V.P. 1970. Estimation of soil moisture and surface runoff for small agricultural watersheds. M.Sc. Thesis. University of Guelph, Guelph, ON.
- Smith, J.H. and J.R. Peterson. 1982. Recycling of nitrogen through land application of agricultural, food processing, and municipal wastes. *In* F.J. Stevenson [Ed.]. *Nitrogen in Agricultural Soils*. Am. Soc. Agron. Madison, WI.
- Sutton, A.L., D.W. Nelson, D.T. Kelly and D.L. Hill. 1986. Comparison of solid vs. liquid dairy manure applications on corn yield and soil composition. *J. Environ. Qual.* 15:370-375.
- Tel, D.A. and C. Heseltine. 1990a. The analyses of KCL soil extracts for nitrate, nitrite and ammonium using a TRAACS 800 autoanalyzer. *Commun. in Soil Sci. Plant Anal.* 21:1681-1688.
- Tel, D.A. and C. Heseltine. 1990b. Chloride analysis of soil leachate using the TRAACS 800 analyzer. *Commun. in Soil Sci. Plant Anal.* 21:1689-1693.
- Thomas, G.W. and W.W. Frye. 1984. Fertilizer and liming. *In* R.E. Phillips and S.H. Phillips. [Eds.]. *No Tillage Agriculture*. van Nostrand Reinhold Co., New York.

- Thomas, R.L., R.W. Sheard and J.R. Moyer. 1967. Comparison of conventional and automated procedures for N, P and K analysis of plant material using a single digestion. *Agron. J.* 59:240-243.
- Tiedje, J.M. 1988. Ecology of denitrification and dissimilatory nitrate reduction to ammonium. Pp 174-244 *In* A.J.B. Zehnder [Ed.]. *Biology of anaerobic microorganisms*. John Wiley & Sons., New York.
- Topp, G.C., J.L. Davis and A.P. Annan. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resour. Res.* 16:574-582.
- Van der Heijden, C.A. and G.K. Montizaan. 1988. Nitrates in drinking water: Health effects and risk. *Human Toxicology*. 7:53-54.
- Van der Molen, J., H.G. Van Fassen, M.Y. Leclerc, R. Vriesema and W.J. Chadon. 1990. Ammonia volatilization from arable land after application of cattle slurry. I. Field estimates. *Neth. J. Agric. Sci.* 38:145-158.
- Van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892-898.
- Van Veen, J.A., and E.A. Paul. 1981. Organic carbon dynamics in grassland soils. I. Background information and computer simulation. *Can. J. Soil Sci.* 61:185-201.
- Van Wesenbeeck, I.J. and R.G. Kachanoski. 1991. Spatial scale dependence of in situ solute transport. *Soil Sci. Soc. Am. J.* 55:3-7.
- Van Wesenbeeck, I.J. 1987. Spatial and temporal dynamics of soil water content under a corn crop. M.Sc. Thesis. University of Guelph, Guelph, ON.
- Voroney, R.P., J.P. Winter and R.P. Beyaert. 1993. Microbial Biomass. *In* M.R. Carter [Ed.]. *Soil Sampling and Methods of Analysis*. Can. Soc. Soil Sci.
- Voroney, R.P. and E.A. Paul. 1984. Determination of a  $k_C$  and  $k_N$  in situ for calibration of the chloroform fumigation incubation method. *Soil Biol. Biochem.* 16: 335-345.
- Wagenet, R.J. and Hutson, J.L. 1989. LEACHM: Leaching Estimation and Chemistry Model. Dept. of Agron. Cornell University. Ithaca, N.Y.
- Wallingford, G.W., L.S. Murphy, W.L. Powers and H.L. Manges. 1975. Denitrification in soil treated with beef feedlot manure. *Commun. Soil Sci. Plant Anal.* 6: 147-161.
- Weier, K.L. and I.C. MacRae. 1992. Denitrifying bacteria in the profile of a Brigalow clay soil beneath a permanent pasture and a cultivated crop. *Soil Biochem.* 24:919-923.
- Witherspoon, D.F. and H.D. Ayers. 1958. Measuring watershed runoff in Ontario. *Agric. Engineering*. 39:403-405.
- Working Committee of the OFGQS. 1992. Ontario farm groundwater quality survey - winter 1991/92. A report prepared for Agriculture Canada, Agri-Food Development Branch, Guelph, ON.
- Yeomans, J.C., J.M. Bremner and G.W. McCarty. 1992. Denitrification capacity and denitrification potential of subsurface soils. *Commun. Soil Sci. Plant Anal.* 23: 919-927.



Younie, M.F. 1993. Chloride and nitrate transport through a sandy soil. M.Sc. Thesis. University of Guelph, Guelph, ON.

Appendix 1: Soil water content ( $\text{cm}^3 \text{cm}^{-3}$ ) measured throughout the experiment at the 0 - 40 and 0 - 80 cm depths.

Soil Water Content ( $\text{cm}^3 \text{ cm}^{-3}$ ) \*.

Date	Depth**		Date	Depth	
	0 - 40	0 - 80		0 - 40	0 - 80
4-Jul-91	0.3059	0.3084	11-Jun-93	0.3920	0.3691
11-Jul-91	0.3619	0.3654	14-Jun-93	0.3302	0.3333
17-Jul-91	0.2990	0.3085	16-Jun-93	0.3232	0.3266
24-Jul-91	0.2817	0.2980	18-Jun-93	0.3190	0.3278
31-Jul-91	0.3048	0.2885	21-Jun-93	0.4364	0.3882
7-Aug-91	0.3344	0.3226	23-Jun-93	0.3912	0.3654
14-Aug-91	0.2930	0.3154	25-Jun-93	0.3464	0.3413
21-Aug-91	0.3418	0.3135	28-Jun-93	0.3396	0.3434
2-Oct-91	0.2891	0.3024	30-Jun-93	0.3190	0.3282
21-May-92	0.3515	0.3576	2-Jul-93	0.3061	0.3214
25-May-92	0.3595	0.3531	5-Jul-93	0.2758	0.3134
26-May-92	0.3186	0.3089	7-Jul-93	0.3119	0.3204
27-May-92	0.3296	0.3125	9-Jul-93	0.3019	0.3067
29-May-92	0.3195	0.3030	12-Jul-93	0.4054	0.3771
1-Jun-92	0.3806	0.3316	14-Jul-93	0.3709	0.3608
2-Jun-92	0.3692	0.3301	16-Jul-93	0.3634	0.3480
3-Jun-92	0.3561	0.3243	19-Jul-93	0.3858	0.3585
4-Jun-92	0.3485	0.3102	21-Jul-93	0.3757	0.3665
5-Jun-92	0.3627	0.3262	23-Jul-93	0.3400	0.3363
8-Jun-92	0.3735	0.3615	26-Jul-93	0.3967	0.3544
9-Jun-92	0.3662	0.3388	28-Jul-93	0.3628	0.3492
10-Jun-92	0.3599	0.3309	30-Jul-93	0.3550	0.3402
11-Jun-92	0.3492	0.3259	3-Aug-93	0.3066	0.3075
12-Jun-92	0.3396	0.3172	5-Aug-93	0.3306	0.3271
15-Jun-92	0.3280	0.3047	9-Aug-93	0.3007	0.3031
17-Jun-92	0.3161	0.2967	11-Aug-93	0.3142	0.3105
18-Jun-92	0.3626	0.3271	13-Aug-93	0.2722	0.2969
19-Jun-92	0.3969	0.3432	16-Aug-93	0.2922	0.2960
22-Jun-92	0.3757	0.3334	18-Aug-93	0.2678	0.2861
23-Jun-92	0.3551	0.3178	20-Aug-93	0.2753	0.2851
24-Jun-92	0.3899	0.3414	23-Aug-93	0.2426	0.2591
26-Jun-92	0.3707	0.3343	25-Aug-93	0.2435	0.2655
30-Jun-92	0.3249	0.3009	27-Aug-93	0.2175	0.2497
1-Jul-92	0.3299	0.3007	30-Aug-93	0.2870	0.2856
2-Jul-92	0.3085	0.2927	1-Sep-93	0.2738	0.2846
3-Jul-92	0.3216	0.3049	3-Sep-93	0.3447	0.3177
6-Jul-92	0.3175	0.3017	8-Sep-93	0.3384	0.3168
9-Jul-92	0.3817	0.3313	15-Sep-93	0.3869	0.3527
10-Jul-92	0.3638	0.3269	17-Sep-93	0.3558	0.3252
13-Jul-92	0.4160	0.3851	22-Sep-93	0.3194	0.2863
15-Jul-92	0.4145	0.3902	1-Oct-93	0.3577	0.3187
16-Jul-92	0.3557	0.3781	14-Oct-93	0.3658	0.3296
20-Jul-92	0.3956	0.3704	18-Oct-93	0.3899	0.3557
21-Jul-92	0.3741	0.3617	22-Oct-93	0.3848	0.3559
22-Jul-92	0.3687	0.3562	26-Oct-93	0.3633	0.3408
24-Jul-92	0.3681	0.3480	28-Oct-93	0.3619	0.3400
27-Jul-92	0.3747	0.3459	8-Nov-93	0.3731	0.3403
28-Jul-92	0.3634	0.3326	12-Nov-93	0.3630	0.3490
30-Jul-92	0.3487	0.3273	2-Dec-93	0.4171	0.3680
4-Aug-92	0.3901	0.3579	6-Dec-93	0.3875	0.3783
5-Aug-92	0.4726	0.4451	14-Dec-93	0.3832	0.3775
6-Aug-92	0.3632	0.3337			
7-Aug-92	0.3488	0.3301			
10-Aug-92	0.3822	0.3572			
11-Aug-92	0.3999	0.3670			
12-Aug-92	0.3851	0.3525			
14-Aug-92	0.3890	0.3571			
17-Aug-92	0.3879	0.3561			
18-Aug-92	0.3832	0.3567			
19-Aug-92	0.3905	0.3569			
21-Aug-92	0.3713	0.3431			
25-Aug-92	0.3382	0.3241			
26-Aug-92	0.3211	0.3169			
16-Sep-92	0.3472	0.3357			
9-Dec-92	0.2398	0.2604			
23-Apr-93	0.3105	0.3041			
27-Apr-93	0.3246	0.3250			
30-Apr-93	0.3180	0.3217			
3-May-93	0.2690	0.2886			
5-May-93	0.3037	0.3268			
13-May-93	0.2758	0.2949			
17-May-93	0.3033	0.3126			
19-May-93	0.3176	0.3161			
21-May-93	0.3077	0.3182			
25-May-93	0.3752	0.3573			
27-May-93	0.3546	0.3355			
1-Jun-93	0.3777	0.3630			
3-Jun-93	0.3452	0.3332			
7-Jun-93	0.3489	0.3471			
9-Jun-93	0.3971	0.3672			

\* These values are the means of 5 different sampling locations.

\*\* Note that the 0 - 40 cm depth was 0 - 70 cm in 1991.

Appendix 2: Decoding Program for Meteorological Files, Elora Research Station  
Evapotranspiration Model and Model Description.

'Programme: Decode  
'March 1, 1993  
'Written by Michael Younic

This programme reads in a raw hourly weather data file, from a CR21X datalogger and decodes the data into an output file which can be used as an input file to the Elora Research Station evapotranspiration model.

'A raw data file consists of the following columns of parameters  
'1) identifier: 0223 or 0225 - hourly value, 0241 - 8 AM Summary  
'0244 - 4PM Summary  
'2 ) Julian Day  
'3 ) Hour  
'4 ) Air Temp. (Rosemount)  
'5 ) Air Temp. (Rotronic)  
'6) Relative Humidity  
'7 ) Depth to Water Table  
'8 ) Solar Radiation (MJ/m2)  
'9) Net Radiation (MJ/m2)  
'10) Mean Wind Speed (km/min)  
'11) Mean Wind Vector Magnitude (km/min)  
'12) Mean Wind Vector Direction  
'13) Standard Deviation of Direction  
'14) Total Rainfall  
'15) Average Temperature for last hour  
'16) Average Relative Humidity for last hour  
'17) # scans in last period

'The output file can be specified by inputting which fields need to be saved to the output file. Only choices 2-16 are allowed.  
'The first time the program is run; the decoded data will be saved to an output file. If there are more files to be decoded for the same time period of interest, the user can specify that these files be appended to the first file. This will produce one long file from several monthly files of original climate data.

This program should be used before running the Elora evapotranspiration program. The default printing gives those variables that are required by the Elora evapotranspiration model. Note that the above list is only valid for CR21X files after Sept. 27, 1987. The dewpoint temperature rather than the relative humidity was given before this date. Also check if the CR21X data files have a space before the carriage return at the end of each line. If there is a space then keep 1 space between the quotes in line 100. If there is no space at the end of the line, put two spaces between the quotes.

```
CHDIR "H. M. S. Victory:ELORA:Climate:ERSmodel:Monthly86"  
CALL TEXTFONT(4)  
CALL TEXTSIZE(12)
```

```
DIM STATIC Rowstring$(80),line1$(80),line2$(80)  
DIM STATIC kb1$(5),kb2$(5)  
DIM STATIC Matrix(1000,15),Col(20)  
CLS
```

```

LOCATE 10,2:PRINT "Would you like to use the default print options (Y/N) ?",kb1$
INPUT kb1$
kb$=UCASE$(kb1$)
IF kb$ = "Y" THEN
Col(1)=1
Col(2)=2
Col(3)=3
Col(4)=5
Col(5)=6
Col(6)=7
Col(7)=8
Col(8)=9
Col(9)=13
Fields=9
CLS
GOTO 5
END IF

```

```

CLS
LOCATE 1,5:PRINT "CHOICES FOR FIELDS IN OUTPUT FILE"
LOCATE 3,3:PRINT "1) Julian Day"
LOCATE 4,3:PRINT "2) Hour"
LOCATE 5,3:PRINT "3) Air Temp. (Rosemount)"
LOCATE 6,3:PRINT "4) Air Temp. (Rotronic)"
LOCATE 7,3:PRINT "5) Relative Humidity"
LOCATE 8,3:PRINT "6) Depth to Water Table"
LOCATE 9,3:PRINT "7) Solar Radiation (MJ/m2)"
LOCATE 10,3:PRINT "8) Net Radiation (MJ/m2)"
LOCATE 11,3:PRINT "9) Mean Wind Speed (km/min)"
LOCATE 12,3:PRINT "10) Mean Wind Vector Magnitude (km/min)"
LOCATE 13,3:PRINT "11) Mean Wind Vector Direction"
LOCATE 14,3:PRINT "12) Standard Deviation of Direction"
LOCATE 15,3:PRINT "13) Total Rainfall"
LOCATE 16,3:PRINT "14) Average Temperature for last hour"
LOCATE 17,3:PRINT "15) Average Relative Humidity for last hour"

```

```

LOCATE 19,3:PRINT "Input the number of fields you want in the output file ";
INPUT Fields
FOR L=1 TO Fields
    PRINT "Input required column number";L;"from the above list and hit RETURN ";
    INPUT Col(L)
NEXT L

```

```

5 PRINT "Input the name of the file to be decoded "; INPUTFILE$;
INPUT INPUTFILE$
PRINT "Is this the first month for the time period of interest (y/n)";kb2$;
INPUT kb2$
PRINT "Input the name of the output file for the decoded data "; OUTPUTFILE$;
INPUT OUTPUTFILE$

```

```

OPEN INPUTFILE$ FOR INPUT AS #1

```

```

kb2$=UCASE$(kb2$)

```

```

IF kb2$ = "N" THEN GOTO 10 ELSE
10   OPEN OUTPUTFILE$ FOR OUTPUT AS #2:GOTO 20
    OPEN OUTPUTFILE$ FOR APPEND AS #2

20   ctr = 0
30   WHILE NOT EOF(1)
        LINE INPUT #1, line1$
        TableID$=MID$(line1$,4,4)
        IF TableID$="0225" THEN
100          LINE INPUT #1,line2$
            Rowstring$=line1$+" "+line2$
        ELSE
            GOTO 30
        END IF
        ctr = ctr +1
        FOR J=1 TO 15
            Matrix(ctr,J)=VAL(MID$(Rowstring$,(J-1)*10+13,6))
        NEXT J
    WEND
    FOR I = 1 TO ctr
        FOR h= 1 TO Fields -1
            PRINT Matrix(I,Col(h));
            PRINT #2, Matrix(I,Col(h)),
        NEXT h
        PRINT Matrix(I,Col(Fields))
        PRINT #2, Matrix(I,Col(Fields))
    NEXT I
    CLOSE #1
    CLOSE #2
END

```

# ELORA RESEARCH STATION POTENTIAL EVAPOTRANSPIRATION MODEL

## 1 INTRODUCTION

Estimates of potential evapotranspiration amounts are required by computer models that attempt to characterize the water balance of field soils. This model is designed to estimate potential evaporation, E, potential transpiration, T, and their sum, potential evapotranspiration, PET, from a field soil prior to the planting of corn (*Zea Mays* L.) through to the time of first frost (approximately April 1 - September 15). The model uses meteorological data, measured on an hourly basis at the Elora Research Station (ERS), to estimate T and E using several proven equations. The model is based on the theory and assumptions discussed in two previous models, MICROSIM and SIMCOY, that have been used at the same site but for slightly different purposes (Place and Brown, 1987; Brown and Gillespie, 1990).

The growing season is divided into three periods:

- 1) Pre-emergence
- 2) Emergence to the end of senescence
- 3) End of senescence to first frost

The output of the model includes values of E, T and PET as well as two files that can be used in conjunction with two soil water models to estimate soil water content and the flux of water out of the root zone. A detailed description of how E and T is calculated in each of these periods, a description of the input parameters and a description of output files follows. Wherever possible, the variable names that are used in the model code will be used here.

## 2 INPUT PARAMETERS

The meteorological parameters that are required by the model must be given for each hour of simulation. The data is collected at the ERS using a CR21X datalogger (Campbell Scientific). These files contain the measured data as well as codes which identify each value in the files. The use of the programme DECODE will ensure that the data is extracted properly from the CR21X files and saved to another text file. This file can then be used as the input file for the model



described here. A list of the required parameters is given in Table 1. The user must be careful to have the parameters in the proper units and that they appear in the same order as shown from top to bottom in Table 1.

Table 1: Required input meteorological data

Variable Name	Definition	Units
JDay	Julian Day	
Hour	Ranges from 0 to 23 in increments of 1	
T	Temperature	(°C)
RH	Relative Humidity	(%)
WT	Depth to water table	(cm)
Rsol	Solar Radiation	(MJ m <sup>-2</sup> )
Rnet	Net Radiation	(MJ m <sup>-2</sup> )
Wspeed	Wind Speed	(km min <sup>-1</sup> )
Rain	Rainfall in the last hour	(mm)

In addition to the measured meteorological data and I / O file names, several other parameters must be specified by the user (Table 2).

Table 2: User specified input parameters.

Variable Name	Definition	Units
FirstDay	First day of simulation	
LastDay	Last day of simulation	
Emerg	Julian Day of emergence	
Senes	Julian Day of senescence	
aLAI, bLAI, LAImat	3 leaf area index coefficients *	
aCPHT, bCPHT, CPHTmat	3 crop height coefficients *	
LAI <sub>max</sub>	maximum leaf area index	
CPHT <sub>max</sub>	maximum crop height	(m)

\* See below for explanation

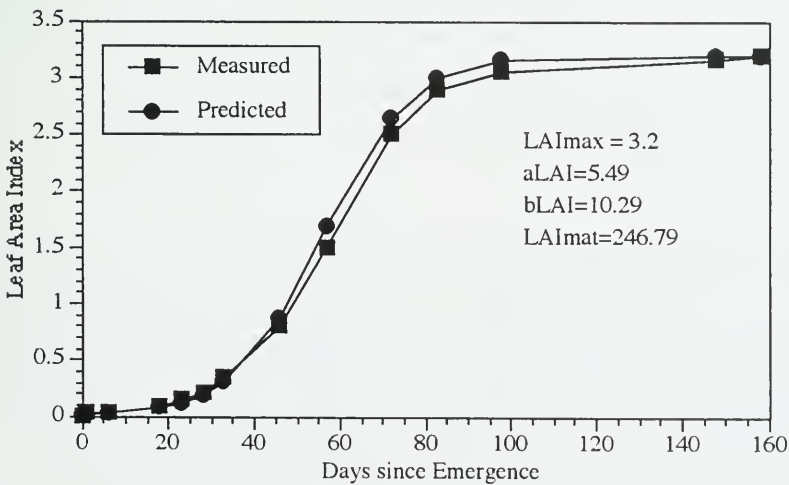


LAI and crop height influence the amount of net radiation reaching the soil surface and the wind pattern over the soil surface, respectively. Therefore the values of leaf area index (LAI) and crop height versus time during the growing season are required to make estimates of PET from cropped surfaces. The increase of LAI and crop height over the length of the growing season have been represented by a sigmoidal equation such as:

$$LAI = \frac{LAI_{max}}{1+\exp\left\{aLAI-\left(bLAI-\frac{T}{LAI_{mat}}\right)\right\}} \tag{1}$$

where LAI<sub>max</sub> is the maximum LAI, T is Julian Day and aLAI, bLAI and LAI<sub>mat</sub> are constants. The constants can be obtained by nonlinear curve fitting of Eq. [1] to a set of measured LAI data to obtain the best fit parameters. Crop height can be described with the same equation using a maximum crop height, CPHT<sub>max</sub>, and fitting for the parameters aCPHT, bCPHT and CPHT<sub>mat</sub>. Figure 1 gives a plot of measured LAI data and Eq. [1] using the specified best fit values.

Figure 1: Measured versus predicted LAI using Eq. [1].



### 3 CALCULATION OF POTENTIAL EVAPORATION AND POTENTIAL TRANSPIRATION

Evaporation and transpiration are only calculated when it is not raining and when the solar and net radiations are greater than 0. The daily evapotranspiration is calculated by adding the hourly amounts of evapotranspiration. Note that in addition to calculating E and T during the different stages of crop growth, the Priestley-Taylor equation is used to calculate PET throughout the time period of interest, simply as a comparison.

#### 3.1 PRE-EMERGENCE

Prior to emergence, E is calculated using the Priestley - Taylor equation and is thus the same value as mentioned above. The Priestley - Taylor equation is given as (Priestley and Taylor, 1972):

$$\text{Evaplat} = \alpha \left( \frac{S}{S + P_{\text{sync}}} \right) (R_{\text{net}} - G_0) \quad [2]$$

where Evaplat is the latent heat flux density ( $\text{W m}^{-2}$ ), S is the slope of the saturated vapour pressure versus temperature curve ( $\text{Pa } ^\circ\text{C}^{-1}$ ),  $R_{\text{net}}$  is net radiation ( $\text{W m}^{-2}$ ),  $P_{\text{sync}}$  is the psychrometric constant ( $66.2 \text{ Pa } ^\circ\text{C}^{-1}$  @  $20^\circ\text{C}$ ) and  $\alpha$  is the Priestley - Taylor coefficient which accounts for aerodynamic effects and is set equal to 1.26. The soil heat flux,  $G_0$  ( $\text{W m}^{-2}$ ), is assumed to be equal to 10 % of the net radiation.

#### 3.2 EMERGENCE TO END OF SENESCENCE

As a row crop grows, the soil surface becomes shaded and evaporation decreases. Conversely, the crop intercepts more net radiation and transpiration increases. The energy available for evapotranspiration can be partitioned into energy for transpiration and energy for evaporation. Ritchie (1972) partitioned the energy based on the leaf area index with the equation:

$$R_{netSoil} = R_{net} e^{(-0.4 LAI)} \quad [3]$$

where  $R_{netSoil}$  is the net radiation available for evaporation. Evaporation was calculated using Eq. [1] with  $R_{net}$  equal to the reduced  $R_{netSoil}$  from Eq. [3]. The net radiation available for transpiration,  $R_{netTran}$ , is equal to the difference between  $R_{net}$  and  $R_{netSoil}$ . Potential transpiration is then calculated using the modified Penman-Monteith equation (Monteith and Unsworth, 1990):

$$Tranlat = \frac{S (R_{netTran} - G_{OTran}) + \left( \frac{C_p \rho_{air} VPD}{R_a} \right)}{(S + P_{syc}) \left( \frac{R_a + R_c}{R_a} \right)} \quad [4]$$

where  $Tranlat$  is the latent heat flux density ( $W m^{-2}$ ),  $\rho_{air}$  is the density of air at the given temperature,  $C_p$  is the specific heat of air at 20 °C,  $VPD$  is the vapour pressure deficit,  $G_{OTran}$  is the soil heat flux equal to 10 % of  $R_{netTran}$  and  $R_a$  and  $R_c$  are the aerodynamic and crop canopy resistances ( $s m^{-1}$ ), respectively.  $R_a$  is calculated using:

$$R_a = \frac{Ln \left( \frac{Z_{wind} - d}{Z_{om}} \right)^2}{W_{speed} K^2} \quad [5]$$

where  $Z_{wind}$  (m) is the height that the wind speed was measured at,  $Z_{om}$  (m) is the surface roughness parameter and  $d$  (m) is the zero plane displacement. For bare soil,  $Z_{om}$  and  $d$  are 0.005 m and 0 m, respectively and for cropped soils  $Z_{om}$  and  $d$  are 0.13 times crop height and 0.64 times crop height, respectively.  $W_{speed}$  is the wind speed ( $m s^{-1}$ ) and  $K$  is the Von Karman constant equal to 0.4. The crop canopy resistance,  $R_c$ , is related to the stomatal resistance and has been reviewed by Brown and Gillespie (1990).  $Evaplat$  and  $Tranlat$ , in Eqs. [2] and [4], are changed to

units of  $\text{mm hr}^{-1}$  by dividing by the latent heat of vapourisation ( $2.45 \times 10^6 \text{ J kg}^{-1}$ ) and multiplying by the number of seconds in an hour.

### 3.3 END OF SENESCENCE TO FIRST FROST

By the end of senescence, the crop is transpiring in negligible amounts and evaporation from the soil surface dominates over transpiration. However, evaporation amounts will also be relatively small since the crop is still standing and covering the soil surface. In this way, the crop is acting as a mulch. Therefore, the incoming net radiation can be partitioned in the same way as in the previous stage but only the evaporation will be considered. The net radiation at the soil surface,  $R_{\text{netSoil}}$ , is used in conjunction with Eq. [2] to calculate the evaporation loss.

## 4 MODEL OUTPUT

Three text files are output from the model. The first file contains the daily amounts of E, T and their sum, PET. The second and third output files can be used as input files to two soil water models. The second file contains the data necessary to run the soil water model, LEACHW, of the Leaching Estimation and Chemistry Model (LEACHM) (Wagenet and Hutson, 1989). The third file contains the data necessary to run the soil water model, SWATRE (Belmans et al., 1983). The SWATRE model can be run under three different options:

- 1) SWATRE can calculate PET using climate data and Priestley Taylor equation.
- 2) SWATRE can calculate PET using climate data and modified Penman-Monteith equation.
- 3) SWATRE can use the PET values calculated from this model.

The choice of which option is used depends on the user but all of the information for any option is contained in the SWATRE output file. The user needs only to cut out whatever information will not be used for that particular run.

## 5 SUMMARY

In summary, a computer model was developed to estimate potential evapotranspiration amounts during the growing season of a corn crop. These values were required as inputs into two soil water models which were used to estimate the soil water content and soil water flux out of the root zone.

Potential evaporation, prior to corn emergence, was estimated using the Priestley - Taylor equation. The net radiation was partitioned, according to the leaf area index, between energy available for potential evaporation and potential transpiration. Again, potential evaporation was estimated using the Priestley - Taylor equation. Potential transpiration was estimated using the modified Penman - Monteith equation. Potential evaporation, after crop senescence, was estimated using the Priestley - Taylor equation and the partitioning of net radiation as discussed above. However, transpiration after senescence was considered to be negligible.

The estimates of potential evapotranspiration agree well with other results presented in the literature for this area of southern Ontario. Limitations of the model include the fact that these estimates are for potential evapotranspiration and may be overestimating the actual evaporation when droughty conditions prevail. In addition, senescence is treated as one point in time when in reality, it takes place over several weeks so that the estimated PET values near and slightly before senescence may be overestimated. Also, LAI is known to decrease slightly after senescence and this too was not accounted for. However, it is felt that these are negligible differences as there are inherent difficulties with predicting PET using the techniques described above.

## 6 REFERENCES

- Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil:SWATRE. *J. Hydrol.* 63:271-286.
- Brown, R.D. and T.J. Gillespie. 1990. Estimating crop top climates from weather station data. *Atmosphere - Ocean.* 29:110-132.
- Monteith, J.L. and M.H. Unsworth. 1990. *Principles of Environmental Physics.* Edward Arnold, London. 241 pp.

- Place, R.E. and D.M. Brown. 1987. Modelling corn yields from soil moisture estimates: description, sensitivity analysis and validation. *Agric. and Forest Meteor.* 41:31-56.
- Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large - scale parameters. *Monthly Weather Review.* 100:81-92.
- Ritchie, J. 1972. Model for predicting evaporation from a row crop with incomplete cover. *Water Resour. Res.* 8:1204-1213.
- Wagenet, R.J. and J.L. Hutson. 1989. LEACHM: Leaching Estimation and Chemistry Model. Dept. of Agron. Cornell University. Ithaca, N.Y.



\*\*\*\*\*

# POTENTIAL EVAPORATION AND EVAPOTRANSPIRATION MODEL FOR THE ELORA RESEARCH STATION

Written by M.F. Younie, March 1993.

Programme: ERSPOTEVAP

This programme was written on an Apple Macintosh IIsi personal computer using  
Microsoft Quickbasic version 1.0 E.

This programme is used to calculate potential evaporation and  
potential transpiration for a field soil from the time prior to  
planting to the time of harvest. See model description for assumptions  
and methodology.

The program will save data that is needed as input for the models  
LEACHW and SWATRE to individual output files. These models can  
then be used to solve Richard's Equation and give estimates of actual  
evaporation and transpiration as well as the soil water contents  
of the various profile depths throughout the growing season.

All of the equations use hourly values from an input file derived from  
the Elora CR21X datalogger files. These files can be decoded and saved  
to a text file using the programme 'Decode'.

Along with the input and output text file names, the user must specify:

- 'starting date
- 'ending date
- 'emergence date
- 'end of senescence date
- 'plant density (#plants/ha)
- 'leaf area index (LAI) coefficients
- 'maximum LAI
- 'crop height coefficients
- 'maximum crop height

LAI and crop height coefficients are derived by fitting a sigmoidal  
equation to measured data using nonlinear techniques (see model  
description)

\*\*\*\*\*

'start of programme code

CALL TEXTFONT(4)            'Changing to a monospaced font - size 12  
CALL TEXTSIZE(12)

'setting directory path for I/O files  
CHDIR "H. M. S. Victory:ELORA:Climate:ERSmodel:Monthly86"

'Dimensioning variables

leng=365

DIM STATIC SHARED InputFile\$, outfile\$,false,true,FirstDay,LastDay  
DIM STATIC SHARED Jday(leng,24),DayEvap(leng),Ra(leng,24),DayTran(leng)  
DIM STATIC SHARED Zom(leng),Zwind,d(leng),PlantDens,AnotheRun  
DIM STATIC SHARED AlreadyDisplay,l,hr,ea(leng,24)  
DIM STATIC SHARED Rho(leng,24),S(leng,24),ChangingInput

```

DIM STATIC SHARED K,Press,Mair,R,Latent,Cp,Psyc,Emerg
DIM STATIC SHARED aLAI,bLAI,LAITmat,aCPHT,bCPHT,CPHTmat,Senes
DIM STATIC SHARED T(leng,24),RH(leng,24),WT(leng,24),Rnet(leng,24)
DIM STATIC SHARED Wspeed(leng,24),Rain(leng,24),GO(leng,24)
DIM STATIC SHARED ctr,Rowstring$(80),LAImax,CPHTmax,NoDays
DIM STATIC SHARED es(leng,24),VPD(leng,24),LAI(leng),Temp(leng,24)
DIM STATIC SHARED NoWeeks,hour(leng,24),RightChoice,Evap(leng,24)
DIM STATIC SHARED RnetSoil(leng,24),GoSoil(leng,24),RnetTran(leng,24)
DIM STATIC SHARED GOTran(leng,24),CropHeight(leng),EvapSoil(leng,24)
DIM STATIC SHARED Rsmin,Rstr,Rcut,Rvstr,Rv(leng,24),J,EvapLat(leng,24)
DIM STATIC SHARED Rs(leng,24),Rc(leng,24),TranLat(leng,24),Tran(leng,24)
DIM STATIC SHARED DayEvapTran(leng),Rsol(leng,24),alpha,count(leng)
DIM STATIC SHARED Value(leng),key$,key1$,week,WTblewk(52)
DIM STATIC SHARED WeekEvapTran(52),counter,kount,StartRain
DIM STATIC SHARED RainIntens(leng),TotRain(leng),MeanT(leng)
DIM STATIC SHARED RnetSum(leng),MeanRH(leng),kounter,MeanWT(leng)
DIM STATIC SHARED EvapPTLat(leng,24),RHSum(leng),MinPressHead(leng)
DIM STATIC SHARED PTEvap(leng,24),DayPTEvap(leng)

```

'Next section declares all constants

false = 0: true = NOT false

ChangingInput = true: AlreadyDisplay = true: RightChoice = false

EndofData = false: Flag = true: AnotherRun = true

openfile=false

InputFile\$ = "clim86"

outfile\$ = "Evap86"

Latent=2.45\*10^6

Psyc=66.2

Cp=1010

K=.4

Press = 98000&

Mair = .029

R = 8.314

MH2O=.018012

g=9.81

alpha=1.26

PlantDens=64000&

aLAI=5.49

bLAI=10.29

LAITmat=246.79

LAImax=3.2

aCPHT=4.93

bCPHT=9.36

CPHTmat=246.1

CPHTmax=3

Emerg=144

Senes=250

FirstDay=121

LastDay=288

ColPos = 55

'Name of input text data file

'Name of output file where results will be written

'Latent heat of vaporization (J/kg)

'Psychrometric Constant at 20 °C (Pa/°C)

'Specific heat of Air at 20 °C (J/kg °C)

'Von Karmann Constant (unitless)

'Atmospheric Pressure (Pa) in summer for Canada

'Molecular Weight of air (kg/mole)

'Universal Gas Law Constant (J/mole °K)

'Molecular weight of water

'Acceleration due to gravity

'Priestley-Taylor coefficient

'Plant density (not used)

'LAI coefficients

'maximum LAI

'Crop Height coefficients

'maximum crop height

'Emergence Julian Day

'Senescence Julian Day

'First day of simulation

'Last day of simulation

```

10 'Start of the main programme
  WHILE ChangingInput
  IF AnotheRun = true THEN
    AnotheRun = false
    CALL DisplayInputs
  END IF

  SOUND 1900,18,180,0

  IF NOT RightChoice THEN
    kb$ = ""
    WHILE LEN(kb$) <= 0
      kb$ = UCASE$(INKEY$)
    WEND
    IF kb$ >= "A" OR kb$ <= "K" THEN RightChoice = true
    IF kb$="S" THEN RightChoice=true 'starts simulation
    IF kb$="Q" THEN 'quits simulation
      ChangingInput = false
    END IF
  END IF

  RightChoice = false

  SELECT CASE kb$
  CASE "A" 'Modifying name of input data file
    LOCATE 3, ColPos: INPUT ; "", InputFile$
    LOCATE 3, ColPos: PRINT " ";
    LOCATE 3, ColPos: PRINT InputFile$;
    kb$ = ""

  CASE "B" 'Modifying name of output data file
    LOCATE 4, ColPos: INPUT ; "", outfile$
    LOCATE 4, ColPos: PRINT " ";
    LOCATE 4, ColPos: PRINT outfile$;
    kb$ = ""

  CASE "C" 'Inputting the first Julian Day of the simulation
    LOCATE 5, ColPos: INPUT ; "", FirstDay
    LOCATE 5, ColPos: PRINT USING "#####"; FirstDay;
    kb$ = ""

  CASE "D" 'Inputting the last Julian Day of the simulation
    LOCATE 6, ColPos: INPUT ; "", LastDay
    LOCATE 6, ColPos: PRINT USING "#####"; LastDay;
    kb$ = ""

  CASE "E" 'Inputting the number of plants per hectare
    LOCATE 7, ColPos: INPUT ; "", PlantDens
    LOCATE 7, ColPos: PRINT USING "#####"; PlantDens;
    kb$ = ""

  CASE "F" 'Inputting the date of emergence
    LOCATE 9, ColPos: INPUT ; "", Emerg
    LOCATE 9, ColPos: PRINT USING "#####"; Emerg;

```

kb\$ = ""

CASE "G" 'Inputting the date of senescence

LOCATE 10, ColPos: INPUT ; "", Senes

LOCATE 10, ColPos: PRINT USING "#####"; Senes;

kb\$ = ""

CASE "H" 'Inputting the three LAI coefficients

LOCATE 11, ColPos: INPUT ; "", aLAI, bLAI, LAITmat

LOCATE 11, ColPos: PRINT USING "###.###"; aLAI, bLAI, LAITmat;

kb\$ = ""

CASE "I" 'Inputting the maximum LAI

LOCATE 13, ColPos: INPUT ; "", LAImax

LOCATE 13, ColPos: PRINT USING "###.###"; LAImax;

kb\$ = ""

CASE "J" 'Inputting the three crop height coefficients

LOCATE 14, ColPos: INPUT ; "", aCPHT, bCPHT, CPHTmat

LOCATE 14, ColPos: PRINT USING "###.###"; aCPHT, bCPHT, CPHTmat;

kb\$ = ""

CASE "K" 'Inputting the maximum crop height

LOCATE 16, ColPos: INPUT ; "", CPHTmax

LOCATE 16, ColPos: PRINT USING "###.###"; CPHTmax;

kb\$ = ""

CASE "S" 'Starting model simulation

CLS

CLOSE

CALL ReadInData

'Calculate potential evaporation prior to emergence with Priestley-Taylor Equation

FOR I=FirstDay TO Emerg-1

DayTran(I)=0

DayEvap(I)=0

DayPTEvap(I)=0

FOR hr=0 TO 23

IF Rain(I,hr)>0 THEN GOTO 30

IF Rnet(I,hr) > 0 AND Rsol(I,hr)>0 THEN

PTEvap(I,hr)=(alpha\*(S(I,hr)/(S(I,hr)+Psysc)))\*(Rnet(I,hr)-

GO(I,hr))) \* 3600 / Latent

Evap(I,hr)=PTEvap(I,hr)

ELSE

Evap(I,hr)=0

PTEvap(I,hr)=0

END IF

DayEvap(I)=Evap(I,hr)+DayEvap(I)

DayPTEvap(I)=PTEvap(I,hr)+DayPTEvap(I)

NEXT hr

DayEvapTran(I)=DayEvap(I)+DayTran(I)

30

NEXT I

'Calculate potential evapotranspiration between emergence and senescence

FOR I=Emerg TO Senes-1

DayEvapTran(I)=0

DayEvap(I)=0

DayTran(I)=0

DayPTEvap(I)=0

FOR hr=0 TO 23

IF Rain(I,hr)>0 THEN GOTO 40

IF Rnet(I,hr) > 0 AND Rsol(I,hr)>0 THEN

net radiation available for transpiration according to the leaf area index

'net radiation available for evaporation

RnetSoil (I,hr)=Rnet(I,hr)\*EXP(-.4 \*LAI(I))

GoSoil(I,hr)=.1\*RnetSoil(I,hr)

'Calculate potential evaporation with Priestley-Taylor equation

EvapLat(I,hr)=alpha\*(S(I,hr)/(S(I,hr)+Psyc))\*(RnetSoil(I,hr)-

GoSoil(I,hr))

Evap(I,hr)=EvapLat(I,hr)\*3600/Latent

'net radiation available for transpiration

RnetTran(I,hr)=Rnet(I,hr)-RnetSoil(I,hr)

GOTran(I,hr)=.1\*RnetTran(I,hr)

'Refer to Brown and Gillespie (1990) for next section

Rsmin = 100 'Minimum stomatal resistance for corn (s/m)

Rstr = 2 \* Rsmin 'Twice the minimum stomatal resistance (s/m)

Rcut=1500 'Cuticular Resistance (s/m)

Rv(I,hr)=.5\*Rsol(I,hr)\*1000000&/3600 'The measured

photosynthetically available radiation (PAR)

Rvstr=50 'The value of Rv(I,hr) such that Rs(I,hr)=twice Rsmin

(W/m2)

'Stomatal resistance to water vapour transfer (s/m) (Norman, 1979)

Rs(I,hr)=(Rsmin\*(Rvstr\*((Rstr/Rsmin)-1)+Rv(I,hr)))/

((Rsmin/Rcut) \* (Rvstr\*((Rstr/Rsmin)-1)+Rv(I,hr))+Rv(I,hr))

'It is assumed that 50% of the total leaf area (0.5 \* LAI) was shaded and does not significantly contribute to transpiration (Szeics and Long, 1969)

Rc(I,hr) = Rs(I,hr)/(0.5 \* LAI(I)) 'Canopy resistance (s/m)

Check to make sure canopy resistance is not greater than maximum

resistance

IF Rc(I,hr) > 520 THEN Rc(I,hr)=520

'Calculate aerodynamic resistance and adjust Ra if the crop is at an

early development stage (Monteith and Unsworth, 1990)

IF CropHeight(I) < .1 THEN

Zwind = 10

d(I)=0

Zom(I)=.005

Ra(I,hr)=LOG(((Zwind - d(I)) / Zom(I)) ^2) / (Wspeed(I,hr)

\* (K ^ 2))

ELSE

```

Zwind = 10!
d(I) = .64 * CropHeight(I)
Zom(I) = .13 * CropHeight(I)
Ra(I,hr)=(LOG((Zwind - d(I)) / Zom(I)) ^2 ) / (Wspeed(I,hr)
* (K ^ 2))
END IF
'Calculate potential transpiration with Penman-Monteith Equation
TranLat(I,hr)=(S(I,hr) * (RnetTran(I,hr) - GOTran(I,hr)) + ((Cp *
Rho(I,hr) * VPD(I,hr)) / Ra(I,hr))) / (S(I,hr) + Psyc * ((Ra(I,hr)+Rc(I,hr))/Ra(I,hr)))
Tran(I,hr)=TranLat(I,hr)*3600/Latent
PTEvap(I,hr)=(alpha*(S(I,hr)/(S(I,hr)+Psyc))*(Rnet(I,hr)-
GO(I,hr)))*3600/Latent
ELSE
Tran(I,hr)=0
Evap(I,hr)=0
PTEvap(I,hr)=0
END IF
DayEvap(I)=Evap(I,hr)+DayEvap(I)
DayTran(I)=Tran(I,hr)+DayTran(I)
DayPTEvap(I)=PTEvap(I,hr)+DayPTEvap(I)
40 NEXT hr
DayEvapTran(I)=DayEvap(I)+DayTran(I)
NEXT I

```

'Calculate potential evaporation with the Priestley-Taylor Equation using the partitioned net radiation and assuming that the crop is acting as a mulch and is no longer transpiring from senescence to the last day

```

FOR I=Senes TO LastDay
DayTran(I)=0
DayEvap(I)=0
DayPTEvap(I)=0
FOR hr=0 TO 23
IF Rain(I,hr)>0 THEN GOTO 50
IF Rnet(I,hr) > 0 AND Rsol(I,hr)>0 THEN
RnetSoil(I,hr)=Rnet(I,hr)*EXP(-.4 *LAI(I))
GoSoil(I,hr)=.1*RnetSoil(I,hr)
'Calculate potential evaporation with Priestley-Taylor equation
EvapLat(I,hr)=alpha*(S(I,hr)/(S(I,hr)+Psyc)) * (RnetSoil(I,hr) -
GoSoil(I,hr))
Evap(I,hr)=EvapLat(I,hr)*3600/Latent
PTEvap(I,hr)=(alpha*(S(I,hr)/(S(I,hr)+Psyc))*(Rnet(I,hr)-
GO(I,hr)))*3600/Latent
ELSE
Evap(I,hr)=0
PTEvap(I,hr)=0
END IF
DayEvap(I)=Evap(I,hr)+DayEvap(I)
DayPTEvap(I)=PTEvap(I,hr)+DayPTEvap(I)
50 NEXT hr
DayEvapTran(I)=DayEvap(I)+DayTran(I)
NEXT I

```

'Now start printing output data to the various output files and screen

OPEN outfile\$ FOR OUTPUT AS #5

J=15

FOR I=FirstDay TO LastDay

DayEvap(I)=0

DayPTEvap(I)=0

DayTran(I)=0

DayEvapTran(I)=0

count(I) =1+15-FirstDay

Value(I)=(count(I)+15-J)/15

IF Value(I) = 1 THEN

PRINT "Day";

PRINT TAB(10);

PRINT "Evap";

PRINT TAB(19);

PRINT "Tran";

PRINT TAB(27);

PRINT "Daily EvapTran";

PRINT TAB(43);

PRINT "Daily PT Evap"

PRINT #5, "Day";

PRINT #5, TAB(10);

PRINT #5, "Evap";

PRINT #5, TAB(19);

PRINT #5, "Tran";

PRINT #5, TAB(27);

PRINT #5, "Daily EvapTran";

PRINT #5, TAB(43);

PRINT #5, "Daily PT Evap"

J=J+15

END IF

FOR hr=0 TO 23

DayEvap(I)=Evap(I,hr)+DayEvap(I)

DayTran(I)=Tran(I,hr)+DayTran(I)

DayPTEvap(I)=PTEvap(I,hr)+DayPTEvap(I)

NEXT hr

DayEvapTran(I)=DayTran(I)+DayEvap(I)

PRINT USING "###"; I;

PRINT TAB(9);

PRINT USING "##.###";DayEvap(I);

PRINT TAB(18);

PRINT USING "##.###";DayTran(I);

PRINT TAB(29);

PRINT USING "##.###";DayEvapTran(I);

PRINT TAB(43);

PRINT USING "##.###";DayPTEvap(I)

PRINT #5, USING "###"; I;

PRINT #5, TAB(9);

PRINT #5, USING "##.###";DayEvap(I);



```

PRINT #5, TAB(18);
PRINT #5, USING "###.###";DayTran(I);
PRINT #5, TAB(29);
PRINT #5, USING "###.###";DayEvapTran(I);
PRINT #5, TAB(43);
PRINT #5, USING "###.###";DayPTEvap(I)

```

NEXT I

```

SOUND 1200,5,180,0
SOUND 1500,6,180,0
SOUND 1900,18.2,180,0

```

CLS

```

'Now output the two files that contain information required to run the SWATRE and
LEACHM soil water models
LOCATE 1,30:PRINT "OUTPUT FILES"
LOCATE 5,5:PRINT "Output files for both the LEACHW and SWATRE models are
written to"
LOCATE 6,1:PRINT "the folder specified above. The LEACHW model uses potential"
LOCATE 7,1:PRINT "evapotranspiration values and depth to water table to estimate soil"
LOCATE 8,1:PRINT "water contents. It also requires data on time, amounts and
intensities"
LOCATE 9,1:PRINT "of rainfall events.
LOCATE 10,5:PRINT "The SWATRE model can calculate potential evapotranspiration or
the "
LOCATE 11,1:PRINT "values can be input into the model. This program outputs
information"
LOCATE 12,1:PRINT "which will allow the user to use SWATRE with the PE calculated"
LOCATE 13,1:PRINT "values (above), calculate PE with the Priestley Taylor Equation"
LOCATE 14,1:PRINT "or calculate PE with the Penman Monteith Equation. All of the
data"
LOCATE 15,1:PRINT "is written to a text file which can be cut and pasted into the
existing"
LOCATE 16,1:PRINT "input files of each model."
LOCATE 20,1:PRINT "Hit return to continue";key$
INPUT key$
CLS

LOCATE 1,30:PRINT "OUTPUT FILE NAMES"
LOCATE 5,1: PRINT "Input the name of the LEACHW output file and hit return ";
INPUT LeachWout$
PRINT "Your LEACHW output file will be called ";LeachWout$
LOCATE 8,1: PRINT "Input the name of the SWATRE output file and hit return ";
INPUT Swatreout$
PRINT "Your SWATRE output file will be called ";Swtareout$
LOCATE 19,1:PRINT" Hit return to continue";key1$
INPUT key1$
CLS

```

```

'Open the LEACHW output file to have the necessary data written to it
OPEN LeachWout$ FOR OUTPUT AS #3
PRINT #3, "LEACHW INPUT FILE DATA"

```





```

PRINT #3,"This is the Day #, Time of Day, Amount and Rain Intensity"
LOCATE 1,25:PRINT "LEACHW INPUT FILE DATA"
PRINT "This is the Day #, Time of Day, Amount and Rain Intensity"
kt=0
FOR I=FirstDay TO LastDay
  kount=0
  TotRain(I)=0
  FOR hr=0 TO 23
    IF Rain(I,hr)>0 THEN
      TotRain(I)=TotRain(I)+Rain(I,hr)
      StopHour=hr
      kount=kount+1
    END IF
  NEXT hr
  IF TotRain(I)>0 THEN
    kt=kt+1
    RainIntens(I)=TotRain(I)/kount*24
    StartRain=(StopHour-kount)/24
    IF StartRain<0 THEN StartRain=0!
    PRINT TAB(17);
    PRINT USING "###";I;
    PRINT TAB(29);
    PRINT USING ".#"; StartRain;
    PRINT TAB(36);
    PRINT USING "##.#";TotRain(I);
    PRINT TAB(45);
    PRINT USING "###.#";RainIntens(I)

    PRINT #3, TAB(17);
    PRINT #3,USING "###";I;
    PRINT #3, TAB(29);
    PRINT #3, USING ".#"; StartRain;
    PRINT #3, TAB(36);
    PRINT #3, USING "##.#";TotRain(I);
    PRINT #3, TAB(45);
    PRINT #3, USING "###.#";RainIntens(I)
  END IF
NEXT I
PRINT #3, "The number of rainfall events is: ";kt;"events"
PRINT "The number of rainfall events is: ";kt;"events"

PRINT #3, " "
PRINT #3, " "
PRINT " "

PRINT #3,"This is the week, evapotranspiration and water table data (mm)"
PRINT "This is the week, evapotranspiration and water table data (mm)"
FOR week=1 TO INT(NoWeeks+1)
  counter=1
  FOR I=FirstDay-7+(week*7) TO LastDay
    WeekEvapTran(week)=WeekEvapTran(week)+DayEvapTran(I)
    WTablewk(week)=WTablewk(week)+(WT(I,0)*10)
    IF counter < 7 THEN counter = counter + 1:NEXT I
  NEXT week

```

```

FOR I=FirstDay+(INT((LastDay-FirstDay+1)/7)*7)+1 TO LastDay
  IF I=LastDay THEN
    PRINT #4, USING "####";I;
    PRINT #4, USING "####.#";MeanWT(I);
    PRINT #4,"/"
    PRINT USING "####";I;
    PRINT USING "####.#";MeanWT(I);
    PRINT "/"
  ELSE
    PRINT #4, USING "####";I;
    PRINT #4, USING "####.#";MeanWT(I);
    PRINT USING "####";I;
    PRINT USING "####.#";MeanWT(I);
  END IF
NEXT I

PRINT "Hit return to continue";key$
INPUT key$
PRINT #4," "
PRINT " "
PRINT #4,"This is the calculated Potential Evaporation and Potential Evapotranspiration"
PRINT "This is the calculated Potential Evaporation and Potential Evapotranspiration"
PRINT "Day    Precip. (cm/day)    Evaporation(cm/day)    Tran(cm/day)    Min
Press Head"
PRINT #4, "Day    Precip. (cm/day)    Evaporation(cm/day)    Tran(cm/day)
Min Press Head"
FOR I = FirstDay TO LastDay
  MinPressHead(I)=((R*(MeanT(I)+273))/(MH2O*g))*LOG(MeanRH(I))
  PRINT #4,USING "####";I;
  PRINT #4, TAB(5):PRINT #4, USING "###.###";TotRain(I)/10;
  PRINT #4,TAB(11):PRINT #4, USING "###.###";DayEvap(I)/10;
  PRINT #4,TAB(17):PRINT #4, USING "###.###";DayTran(I)/10;
  PRINT #4, USING "#####.###";MinPressHead(I)*100
  PRINT USING "####";I;
  PRINT TAB(5):PRINT USING "###.###";TotRain(I)/10;
  PRINT TAB(11):PRINT USING "###.###";DayEvap(I)/10;
  PRINT TAB(17):PRINT USING "###.###";DayTran(I)/10;
  PRINT USING "#####.###";MinPressHead(I)*100
NEXT I
PRINT #4, " "
PRINT " "
PRINT #4, "This section prints the data that SWATRE requires to calculate PE with
Priestley Taylor Eqn"
PRINT "This section prints the data that SWATRE requires to calculate PE with Priestley
Taylor Eqn"
PRINT #4, "Day Precip. (cm/day) Net Radiation (W/m2) Mean Temp. Mean Rel. Hum."
PRINT "Day Precip. (cm/day) Net Radiation (W/m2) Mean Temp. Mean Rel. Hum."
FOR I = FirstDay TO LastDay
  PRINT #4,USING "####";I;
  PRINT #4, TAB(6):PRINT #4, USING "###.###";TotRain(I)/10;
  PRINT #4,TAB(12):PRINT #4, USING "#####.###";RnetSum(I);
  PRINT #4,TAB(23):PRINT #4, USING "###.###";MeanT(I);
  PRINT #4,TAB(29):PRINT #4, USING "###.###";MeanRH(I)

```

```

        PRINT USING "###";I;
        PRINT TAB(6):PRINT USING "###.##";TotRain(I)/10;
        PRINT TAB(12):PRINT USING "#####.##";RnetSum(I);
        PRINT TAB(23):PRINT USING "###.##";MeanT(I);
        PRINT TAB(29):PRINT USING "###.##";MeanRH(I)
NEXT I
PRINT #4," "
PRINT " "
'PRINT #4, "This section prints the data that SWATRE requires to calculate PE with the
Penman-Monteith Eqn"
PRINT " "
PRINT " Hit any key to return to the input menu
kb$=""
WHILE LEN(kb$)<=0
    kb$=INKEY$
WEND
CASE ELSE
END SELECT

AnotheRun = true
WEND
END ' End of programme

SUB DisplayInputs STATIC This is the input screen section

CLS
LOCATE 1,5:PRINT "ERS POTENTIAL EVAPOTRANSPIRATION INPUT SCREEN"
LOCATE 3, 1: PRINT "A. Name of input data file.....: "; InputFile$;
LOCATE 4, 1: PRINT "B. Name of output data file.....: "; outfile$;
LOCATE 5, 1: PRINT "C. First day of simulation.....: ";
PRINT USING "#####"; FirstDay;
LOCATE 6, 1: PRINT "D. Last day of simulation.....: ";
PRINT USING "#####"; LastDay;
LOCATE 7, 1: PRINT "E. Plant density (plants/ha).....: ";
PRINT USING "#####"; PlantDens;
LOCATE 8,5: PRINT "( 0 if no plants )"
LOCATE 9, 1: PRINT "F. Date of Emergence.....: ";
PRINT USING "#####"; Emerg;
LOCATE 10, 1: PRINT "G. Date of Senescence.....: ";
PRINT USING "#####"; Senes;
LOCATE 11, 1: PRINT "H. Three LAI coefficients (a,b,Tmat).....: ";
PRINT USING "###.##"; aLAI,bLAI;;PRINT " ";PRINT USING "###.##";LAI Tmat;
LOCATE 12,5:PRINT "(Best fit LAI coeffs. sep. by commas)"
LOCATE 13, 1: PRINT "I. Maximum LAI.....: ";
PRINT USING "###.##"; LAImax;
LOCATE 14, 1: PRINT "J. Three crop height coefficients (a,b,Tmat).....: ";
PRINT USING "###.##"; aCPHT,bCPHT;;PRINT " ";PRINT USING
"###.##";CPHTmat;
LOCATE 15,5:PRINT "(Best fit crop height coeffs. sep. by commas)"
LOCATE 16, 1: PRINT "K. Maximum crop height.....: ";
PRINT USING "###.##"; CPHTmax;
LOCATE 17, 1: PRINT "Q. Quit";
LOCATE 19, 5: PRINT "Press index letter to change inputs and press RETURN";
LOCATE 20, 5: PRINT "Press S to start simulation or Q to quit"

```

END SUB

SUB ReadInData STATIC This subroutine reads in the data and calculates some common variables and also checks the integrity of the data such as checking for relative humidities above 100 %

```
OPEN InputFile$ FOR INPUT AS #1
WHILE NOT EOF(1)
    ctr=0
    FOR I=FirstDay TO LastDay
        FOR hr = 0 TO 23
            INPUT #I, Jday(I,hr), hour(I,hr), T(I,hr),RH(I,hr),WT(I,hr),
            Rsol(I,hr),Rnet(I,hr), Wspeed(I,hr),Rain(I,hr)
            PRINT Jday(I,hr), hour(I,hr), Wspeed(I,hr), T(I,hr),
            RH(I,hr),WT(I,hr),Rsol(I,hr),Rnet(I,hr),Rain(I,hr)
            ctr=ctr+1
            'Look for problem and missing data
            IF RH(I,hr)>100 AND Rnet(I,hr)>0 AND Rsol(I,hr)>0 AND
            Rain(I,hr)=0 THEN PRINT "Day";I;"has RH >0"
            IF Rnet(I,hr)>0 AND Rsol(I,hr)>0 AND Rain(I,hr)=0 AND
            RH(I,hr)>T(I,hr) THEN PRINT "Day";I;"has RH>T"
            IF RH(I,hr) < 0 AND Rnet(I,hr)>0 AND Rsol(I,hr)>0 AND
            Rain(I,hr)=0 THEN RH(I,hr)=0
            IF RH(I,hr) < 0 AND Rnet(I,hr)>0 AND Rsol(I,hr)>0 AND
            Rain(I,hr)=0 THEN PRINT "Day";I;"has RH<0"

            'set wind speed equal to threshold velocity if recorded as 0.
            IF Wspeed(I,hr)=0 THEN Wspeed(I,hr)=.015
            IF Wspeed(I,hr)=0 THEN PRINT "Day";I;"has Wspeed=0"
            IF WT(I,hr)<=0 THEN PRINT "Day";I;"has WT<=0"
            PRINT Jday(I,hr), hour(I,hr), Wspeed(I,hr)
        NEXT hr
    NEXT I
WEND

'Check if RH is input as dew point temperature and change to %.
This only works if the two temperatures are above 0.
FOR I= FirstDay TO LastDay
    FOR hr=0 TO 23
        IF RH(I,hr)<T(I,hr) THEN
            es(I,hr)=610.8001*EXP((17.269*T(I,hr))/(237.3+T(I,hr)))
            ea(I,hr)=610.8001*EXP((17.269*RH(I,hr))/(237.3+RH(I,hr)))
            RH(I,hr)=(ea(I,hr)/es(I,hr))*100
        END IF
    NEXT hr
NEXT I

NoDays=ctr/24
PRINT "Number of Days in input file is";NoDays; "days."
NoWeeks=NoDays/7
PRINT "Number of Weeks in input file is";NoWeeks; "weeks."
```

SOUND 1976,9.1,127,0

'Calculate saturation and actual vapour pressure and vapour pressure deficit

Temp. The next equation is part of Teten's equation which gives vapour pressure as a function of

$Temp(hr) = EXP((17.269 * T(hr)) / (237.3 + T(hr)))$

The full Teten equation (Pa) is  $610.8001 * Temp$  (above) see (Norman, 1979, p. 261);

BLC p. 55

'Change 610.8001 to 6.108001 for vapour pressure in mbars.

The next equation, S, represents the slope of the saturation vapour pressure curve versus temperature as a function of temperature (Pa/°C)

The equation is the derivative of Teten's equation with respect to temperature.

$S(hr) = 610.8001 * (17.269 / (T(hr) + 237.3) - (17.269 * T(hr)) / ((T(hr) + 237.3)^2)) * Temp(hr)$

FOR I=FirstDay TO LastDay

FOR hr=0 TO 23

$Temp(I,hr) = EXP((17.269 * T(I,hr)) / (237.3 + T(I,hr)))$

$S(I,hr) = 610.8001 * (17.269 / (T(I,hr) + 237.3) - (17.269 * T(I,hr)) / ((T(I,hr) + 237.3)^2)) * Temp(I,hr)$

$es(I,hr) = 610.8001 * Temp(I,hr)$

$ea(I,hr) = (RH(I,hr) / 100) * es(I,hr)$

$VPD(I,hr) = es(I,hr) - ea(I,hr)$

$Rho(I,hr) = (Press * Mair) / ((T(I,hr) + 273) * R)$

$Wspeed(I,hr) = Wspeed(I,hr) * (1000 / 60)$

$Rnet(I,hr) = 1000000 * Rnet(I,hr) / 3600$

$GO(I,hr) = .1 * Rnet(I,hr)$

'PRINT I,hr,GO(I,hr),Temp(I,hr),S(I,hr),VPD(I,hr)

'PRINT Jday(I,hr),hour(I,hr),Wspeed(I,hr)

NEXT hr

$LAI(I) = LAImax / (1 + EXP(aLAI - (bLAI * ((Jday(I,0) - Emerg) / (LAI Tmat - Emerg))))$

IF I < Emerg THEN LAI(I)=0

IF I > Senes THEN LAI(I)=LAImax

$CropHeight(I) = CPHTmax / (1 + EXP(aCPHT - (bCPHT * ((Jday(I,0) - Emerg) / (CPHTmat - Emerg))))$

IF I < Emerg THEN CropHeight(I)=0

IF I > Senes THEN CropHeight = CPHTmax

NEXT I

FOR I= FirstDay TO LastDay

RnetSum(I)=0

RHSum(I)=0

MeanT(I)=0

MeanRH(I)=0

MeanWT(I)=0

kt=0

FOR hr=0 TO 23

IF Rnet(I,hr)>0 AND Rsol(I,hr)>0 THEN

RnetSum(I)=RnetSum(I)+Rnet(I,hr)

END IF

IF RH(I,hr)<100 THEN

kt=kt+1

RHSum(I)=RHSum(I)+RH(I,hr)/100

END IF

MeanT(I)=MeanT(I)+T(I,hr)

MeanWT(I)=MeanWT(I)+WT(I,hr)

NEXT hr

MeanT(I)=MeanT(I)/24

MeanRH(I)=RHSum(I)/kt

```
      RnetSum(I)=RnetSum(I)*1000000&/86400&  
      MeanWT(I)=MeanWT(I)/24  
NEXT I  
CLOSE #1  
END SUB
```

Appendix 3: 1992 LEACHM Input File.



LWERS92 SOIL-WATER-PLANT-INTERACTION SIMULATION  
SIMULATION PERIODS (Data must be present for each item, even if it not used)

-----  
Date type (US:1 UK:2) 2  
Starting date 010492 Ending (date or day no.) 311092  
Read theta(1) or pot'l(2) 1  
No. of water applications 127  
Cycles through data 1 No. of crops 1  
K-Th-h from PSD:yes(1)no(0) 1 Trace 1(on) 0(off) 0  
-----

PROFILE DETAILS

-----  
Profile depth (mm) .1000E+04 Bottom boundary condition 1  
Segment thickness (mm) .1000E+03 :1 or 5,water table depth .2000E+04  
-----

FOR UNIFORM PROFILE: (Any non-zero value here will override those in the  
table of hydrological characteristics below unless K-Th-h calc. from PSD).  
Soil bulk density Mg/cu.m .0000E+00 Air -entry value' kPa -.0000E+04  
Exponent in Campbell's eq .0000E+02 Sat'd K values (mm/day) .0000E+04  
-----

CROP DATA

-----  
Plants present: 1 yes, 0 no 1 Wilting point (soil) kPa -.1500E+04  
Max(actual tran/pot'l tran) .1200E+01 Min.root water pot'l (kPa) -.3000E+04  
Roots: Const(1);growing(2) 2 Max.root water pot'l (kPa) .0000E+00  
If 1: root length (m) .5000E+03 Root flow resistance term .1050E+01  
-----

NUMBER OF OUTPUT FILES

4  
-- .OUT file -----  
----- .SUM file -----  
Summary print interval (d) 1  
Node print frequency 1 Three depth segments for the summary  
Print options: 1, 2 or 3 2 file (0's default to thirds of the  
1: Time intervals/print 1 profile) (mm) :  
2: days/print 1.0 Surface to [depth 1?] 600  
3: No. of prints (even) 4 Depth 1 to [depth 2?] 800  
Tables printed: 1,2 or 3 3 Depth 2 to [depth 3?] 1000  
-----

TIMES AT WHICH \*.OUT FILE IS DESIRED (if print option = 3)

Date or Day no.	Time of day (to nearest tenth)	Date or Day no.	Time of day (to nearest tenth)
122688	.2	122888	.6
010189	.5	010489	.0

\*\*\*\*\*  
Soil Particle size distribution Match K(h) at:  
Layer Clay Silt Rho Organic K Matric Retentivity  
no. % % kg/dm3 carbon mm/d pot'l regression  
model no.  
-----  
1 23. 55. 1.25 1.5 200. 0. 5  
2 23. 55. 1.30 1.5 200. 0. 5  
3 25. 52. 1.54 1.3 150. 0. 5  
4 25. 58. 1.59 1.0 100. 0. 5  
5 25. 52. 1.62 1.0 70. 0. 5  
6 25. 52. 1.70 1.0 30. 0. 5  
7 30. 52. 1.70 1.0 20. 0. 5  
8 30. 52. 1.70 1.0 20. 0. 5  
9 30. 52. 1.70 1.0 20. 0. 5  
10 30. 52. 1.70 1.0 20. 0. 5  
-----

Particle density kg/dm3: Clay Sand Organic matter  
2.65 2.65 1.10

*****						
Soil layer no.	Starting values		Hydrological Characteristics			Root fraction (for const root distr)
	Pot'l or Theta kPa		AEV kPa	BCAM	KS mm/d	
1	-1515.0	0.3000	-.113E+01	2.11	4320.	0.250
2	-1515.0	0.3000	-.156E+01	2.05	4320.	0.300
3	-1515.0	0.3000	-.202E+01	2.00	4061.	0.300
4	-1515.0	0.3000	-.173E+01	1.65	10195.	0.100
5	-1515.0	0.3000	-.108E+01	1.58	10195.	0.050
6	-1515.0	0.3000	-.115E+01	1.75	14774.	0.000
7	-1515.0	0.3000	-.115E+01	1.70	14774.	0.000
8	-1515.0	0.3000	-.115E+01	1.70	14774.	0.000
9	-1515.0	0.3000	-.107E+01	2.00	14774.	0.000
10	-1515.0	0.3000	-.065E+01	3.00	14774.	0.000
*****						

#### CROP DATA

Crop no	Planting Date	Emergence Date	Root no	Maturity Plant	Harvest	Rel. root depth	Crop cover frac	Plants per sq. m	Pan factor
1	160592	240592	150892	220892	141092	0.60	0.9	6.400	1.00
*****									

#### RAIN/IRRIGATION AND WATER COMPOSITION

START		AMOUNT	RATE
Date or	Time of	mm	mm/day
Day no.	Day		
----- (10th) -----			
010492		.3	1.4
040492		.3	0.2
070492		.5	1.0
080492		.3	0.2
100492		.9	0.8
110492		.3	30.0
160492		.0	45.2
170492		.1	0.4
200492		.3	0.2
210492		.5	7.6
220492		.4	1.0
230492		.8	0.8
240492		.7	5.2
250492		.4	7.4
260492		.4	0.4
290492		.8	2.4
300492		.0	3.0
010592		.5	1.4
020592		.5	30.0
050592		.7	0.8
070592		.3	0.2
090592		.5	1.6
130592		.3	0.6
170592		.8	11.8
010692		.5	2.4
040692		.9	0.2
050692		.6	3.4
060692		.7	30.4
070692		.4	3.6
080692		.0	0.2
170692		.9	7.0
180692		.6	20.6
200692		.5	0.2
210692		.5	1.4
220692		.3	0.2
240692		.2	7.2
250692		.3	0.2
260692		.5	4.6

280692	.1	0.2	4.8
300692	.4	0.2	4.8
020792	.9	1.2	28.8
030792	.7	8.8	52.8
040792	.7	0.4	4.8
050792	.6	0.2	4.8
080792	.5	18.2	54.6
100792	.5	11.0	66.0
110792	.0	0.2	4.8
120792	.7	43.8	175.2
130792	.3	0.2	4.8
130792	.0	36.2	41.4
150792	.6	1.4	16.8
160792	.7	0.8	9.6
170792	.3	14.0	33.6
180792	.7	1.6	9.6
190792	.0	0.2	4.8
200792	.3	0.8	19.2
210792	.2	0.2	4.8
230792	.2	3.8	15.2
240792	.3	0.2	4.8
260792	.2	6.0	24.0
270792	.3	0.2	4.8
280792	.9	1.4	33.6
290792	.0	0.2	4.8
300792	.3	0.2	4.8
310792	.2	19.2	38.4
010892	.8	0.4	4.8
020892	.8	4.4	21.1
030892	.5	2.8	22.4
040892	.5	0.2	4.8
050892	.3	0.2	4.8
080892	.6	25.4	87.1
100892	.7	13.2	105.6
110892	.0	0.2	4.8
130892	.0	5.6	16.8
160892	.4	8.2	24.6
180892	.6	6.0	36.0
190892	.2	0.2	4.8
200892	.2	0.2	4.8
220892	.1	0.2	4.8
240892	.5	0.2	4.8
250892	.2	0.2	4.8
260892	.0	0.2	4.8
270892	.5	86.6	207.8
280892	.2	43.2	69.1
290892	.5	0.6	7.2
300892	.3	1.4	33.6
310892	.1	1.2	28.8
020992	.8	0.6	4.8
030992	.0	10.6	50.9
040992	.1	0.2	4.8
060992	.3	8.8	42.2
080992	.5	4.2	33.6
090992	.7	1.6	7.7
100992	.3	7.2	43.2
130992	.1	0.2	4.8
140992	.3	0.2	4.8
150992	.6	0.8	19.2
160992	.4	0.2	4.8
170992	.1	7.6	20.3
180992	.5	20.6	98.9
190992	.3	0.2	4.8
210992	.2	3.6	14.4
220992	.0	10.8	32.4
230992	.3	0.2	4.8
240992	.3	0.2	4.8
270992	.2	3.0	12.0
280992	.5	0.6	4.8
011092	.3	0.2	4.8
071092	.3	0.2	4.8
081092	.0	0.2	4.8

091092	.0	9.4	75.2
101092	.8	1.6	7.7
121092	.6	4.8	23.0
131092	.2	1.0	8.0
141092	.3	0.6	14.4
151092	.3	14.2	26.2
161092	.2	32.4	55.5
171092	.3	0.4	4.8
181092	.5	2.8	13.4
201092	.5	1.8	7.2
211092	.2	1.6	5.5
221092	.3	0.2	4.8
231092	.7	0.6	14.4
261092	.3	0.6	7.2
271092	.3	0.2	4.8
291092	.2	0.2	4.8
301092	.3	0.2	4.8

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POTENTIAL ET (WEEKLY TOTALS, mm) AND DEPTH TO WATER TABLE (mm)

WEEK NO.	ET	WATER TABLE
1	12.0	807.1
2	12.0	633.0
3	8.1	587.4
4	14.0	615.3
5	13.6	643.7
6	27.3	742.2
7	29.6	909.0
8	28.3	986.0
9	25.3	1037.9
10	24.8	1030.4
11	39.1	942.8
12	19.0	1029.1
13	21.9	1152.0
14	26.0	1195.2
15	14.6	1194.3
16	16.3	702.6
17	21.4	876.3
18	18.3	937.7
19	20.7	924.6
20	14.7	854.2
21	22.6	940.3
22	12.2	757.5
23	12.2	654.0
24	5.3	660.6
25	3.2	653.4
26	3.8	653.4
27	4.0	852.7
28	2.6	924.5
29	0.8	716.8
30	1.7	617.2
31	0.8	574.9

Appendix 4: 1992 and 1993 Net Drainage Past the 40 cm and 80 cm Depths as Calculated with the Water Balance Method.

## 1992 net drainage past the 80 cm depth.

Date	Precipitation	Cumulative Precip	AET	Cumulative AET	Storage	Cum Net Drainage
	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)
1-Apr-92	0.140		0.060			
2-Apr-92			0.094			
3-Apr-92			0.199			
4-Apr-92	0.020		0.202			
5-Apr-92			0.224			
6-Apr-92			0.230			
7-Apr-92	0.100		0.193			
8-Apr-92	0.020		0.216			
9-Apr-92			0.251			
10-Apr-92	0.080		0.132			
11-Apr-92	3.000		0.008			
12-Apr-92			0.164			
13-Apr-92			0.183			
14-Apr-92			0.246			
15-Apr-92			0.170			
16-Apr-92	4.520		0.000			
17-Apr-92	0.040		0.071			
18-Apr-92			0.145			
19-Apr-92			0.163			
20-Apr-92	0.020		0.215			
21-Apr-92	0.760		0.052			
22-Apr-92	0.100		0.164			
23-Apr-92	0.080		0.314			
24-Apr-92	0.520		0.162			
25-Apr-92	0.740		0.067			
26-Apr-92	0.040		0.187			
27-Apr-92			0.176			
28-Apr-92			0.334			
29-Apr-92	0.240		0.329			
30-Apr-92	0.300		0.181			
1-May-92	0.140		0.047			
2-May-92	3.000		0.093			
3-May-92			0.285			
4-May-92			0.225			
5-May-92	0.080		0.205			
6-May-92			0.301			
7-May-92	0.020		0.357			
8-May-92			0.426			
9-May-92	0.160		0.176			
10-May-92			0.486			
11-May-92			0.493			
12-May-92			0.486			
13-May-92	0.060		0.346			
14-May-92			0.299			
15-May-92			0.443			
16-May-92			0.493			
17-May-92	1.180		0.442			
18-May-92			0.455			
19-May-92			0.482			
20-May-92			0.449			
21-May-92			0.524		28.604	
22-May-92			0.516			
23-May-92			0.338			
24-May-92			0.316			
25-May-92		0.000	0.391	2.086	28.251	-1.793
26-May-92		0.000	0.191	2.277	24.711	1.616
27-May-92		0.000	0.299	2.575	25.001	1.028
28-May-92		0.000	0.477	3.052		
29-May-92		0.000	0.456	3.508	24.243	0.853
30-May-92		0.000	0.046	3.554		
31-May-92		0.000	0.075	3.630		
1-Jun-92	0.240	0.240	0.429	4.058	26.527	-1.741
2-Jun-92		0.240	0.511	4.569	26.406	-2.131
3-Jun-92		0.240	0.465	5.034	25.946	-2.135
4-Jun-92	0.020	0.260	0.409	5.443	24.815	-1.394
5-Jun-92	0.340	0.600	0.148	5.590	26.098	2.484
6-Jun-92	3.040	3.640	0.222	5.812		
7-Jun-92	0.360	4.000	0.102	5.915		
8-Jun-92	0.020	4.020	0.464	6.379	28.918	-2.673
9-Jun-92		4.020	0.496	6.875	27.106	-1.356
10-Jun-92		4.020	5.23	7.398	26.469	-1.243
11-Jun-92		4.020	0.533	7.931	26.068	-1.375
12-Jun-92		4.020	0.547	8.477	25.379	-1.232
13-Jun-92		4.020	0.571	9.049		
14-Jun-92		4.020	0.472	9.521		
15-Jun-92		4.020	0.470	9.991	24.377	-1.744
16-Jun-92		4.020	0.468	10.459		
17-Jun-92	0.700	4.720	0.440	10.900	23.732	-1.308
18-Jun-92	2.060	6.780	0.358	11.257	26.167	-2.040
19-Jun-92		6.780	0.177	11.434	27.457	-3.507
20-Jun-92	0.020	6.800	0.082	11.516		
21-Jun-92	0.140	6.940	0.070	11.586		
22-Jun-92	0.020	6.960	0.460	12.046	26.675	-3.675
23-Jun-92		6.960	0.301	12.348	25.428	-2.212
24-Jun-92	0.720	7.680	0.095	12.443	27.316	-3.474
25-Jun-92	0.020	7.700	0.302	12.744		
26-Jun-92	0.460	8.160	0.309	13.053	26.746	-3.035
27-Jun-92		8.160	0.403	13.456		
28-Jun-92	0.020	8.180	0.480	13.936		
29-Jun-92		8.180	0.471	14.407		
30-Jun-92	0.020	8.200	0.205	14.611	24.070	-1.877
1-Jul-92		8.200	0.414	15.025	24.056	-2.277
2-Jul-92	0.120	8.320	0.421	15.446	23.414	-1.936
3-Jul-92	0.880	9.200	0.249	15.695	24.388	-2.279

## 1992 net drainage past the 80 cm depth (continued).

Date	Precipitation	Cum. Precipitation	AET	Cumulative AET	Storage	Cum. Net Drainage
	(cm)	(cm)	(cm)	(cm)	(cm)	(cm)
4-Jul-92	0.040	9.240	0.481	16.175		
5-Jul-92	0.020	9.260	0.455	16.631		
6-Jul-92		9.260	0.341	16.971		
7-Jul-92		9.260	0.417	17.388	24.136	-3.243
8-Jul-92	1.820	11.080	0.065	17.453		
9-Jul-92		11.080	0.486	17.939	26.503	-4.758
10-Jul-92	1.100	12.180	0.128	18.067	26.148	-3.431
11-Jul-92	0.020	12.200	0.512	18.578		
12-Jul-92	4.380	16.580	0.161	18.739		
13-Jul-92	0.020	16.600	0.369	19.108	30.806	-4.709
14-Jul-92	3.620	20.220	0.000	19.108		
15-Jul-92	0.140	20.360	0.316	19.423	31.219	-1.678
16-Jul-92	0.080	20.440	0.241	19.664	30.245	-0.865
17-Jul-92	1.400	21.840	0.016	19.680		
18-Jul-92	0.160	22.000	0.297	19.977		
19-Jul-92	0.020	22.020	0.514	20.491		
20-Jul-92	0.080	22.100	0.277	20.768	29.631	0.305
21-Jul-92	0.020	22.120	0.295	21.063	28.938	0.723
22-Jul-92		22.120	0.355	21.418	28.493	0.813
23-Jul-92	0.380	22.500	0.179	21.597		
24-Jul-92	0.020	22.520	0.533	22.130	27.842	1.153
25-Jul-92		22.520	0.523	22.653		
26-Jul-92	0.600	23.120	0.119	22.772		
27-Jul-92	0.020	23.140	0.485	23.256	27.670	0.818
28-Jul-92	0.140	23.280	0.424	23.680	26.611	1.593
29-Jul-92	0.020	23.300	0.378	24.058		
30-Jul-92	0.020	23.320	0.286	24.344		
31-Jul-92	1.920	25.240	0.019	24.364	26.183	1.396
1-Aug-92	0.040	25.280	0.506	24.870		
2-Aug-92	0.440	25.720	0.278	25.148		
3-Aug-92	0.280	26.000	0.332	25.379		
4-Aug-92	0.020	26.020	0.348	25.728	28.634	0.263
5-Aug-92	0.020	26.040	0.433	26.161	27.609	0.875
6-Aug-92		26.040	0.394	26.555	26.699	1.391
7-Aug-92		26.040	0.452	27.007	26.406	1.232
8-Aug-92	2.540	28.580	0.103	27.110		
9-Aug-92		28.580	0.179	27.289		
10-Aug-92	1.320	29.900	0.343	27.632	28.578	2.294
11-Aug-92	0.020	29.920	0.308	27.940	29.362	1.222
12-Aug-92		29.920	0.217	28.157	28.204	2.163
13-Aug-92	0.560	30.480	0.133	28.291		
14-Aug-92		30.480	0.323	28.613	28.565	1.906
15-Aug-92		30.480	0.236	28.849		
16-Aug-92	0.820	31.300	0.045	28.894		
17-Aug-92		31.300	0.301	29.195	28.490	2.219
18-Aug-92	0.600	31.900	0.354	29.549	28.532	2.423
19-Aug-92	0.020	31.920	0.269	29.818	28.555	2.151
20-Aug-92	0.020	31.940	0.425	30.243		
21-Aug-92		31.940	0.437	30.679	27.447	2.417
22-Aug-92	0.020	31.960	0.420	31.099		
23-Aug-92		31.960	0.376	31.476		
24-Aug-92	0.020	31.980	0.215	31.691		
25-Aug-92	0.020	32.000	0.279	31.970	25.932	2.702
26-Aug-92	0.020	32.020	0.293	32.263	25.353	3.008
27-Aug-92	8.660	40.680	0.016	32.279		
28-Aug-92	4.320	45.000	0.006	32.285		
29-Aug-92	0.060	45.060	0.256	32.541		
30-Aug-92	0.140	45.200	0.278	32.819		
31-Aug-92	0.120	45.320	0.284	33.102		
1-Sep-92		45.320	0.293	33.395		
2-Sep-92	0.060	45.380	0.252	33.648		
3-Sep-92	1.060	46.440	0.175	33.823		
4-Sep-92	0.020	46.460	0.370	34.192		
5-Sep-92		46.460	0.342	34.534		
6-Sep-92	0.880	47.340	0.148	34.682		
7-Sep-92		47.340	0.272	34.953		
8-Sep-92	0.420	47.760	0.109	35.062		
9-Sep-92	0.160	47.920	0.210	35.273		
10-Sep-92	0.720	48.640	0.291	35.564		
11-Sep-92		48.640	0.309	35.873		
12-Sep-92		48.640	0.264	36.137		
13-Sep-92	0.020	48.660	0.331	36.468		
14-Sep-92	0.020	48.680	0.282	36.750		
15-Sep-92	0.080	48.760	0.217	36.966		
16-Sep-92	0.020	48.780	0.253	37.220	26.857	13.308





1993 net drainage past the 40 cm and 80 cm depths.

Date	Precipitation	Cumulative Precip.	AET	Cum. AET	Storage (40 cm)	Cum. Net Drainage (40 cm)	Storage (80 cm)	Cum. Net Drainage (80 cm)
	(cm)	(cm)	(cm)	(cm)			(cm)	(cm)
1-Apr-93	0.120		0.029					
2-Apr-93	0.300		0.038					
3-Apr-93	0.140		0.015					
4-Apr-93	0.000		0.128					
5-Apr-93	0.020		0.276					
6-Apr-93	0.000		0.283					
7-Apr-93	0.000		0.299					
8-Apr-93	0.000		0.177					
9-Apr-93	0.560		0.119					
10-Apr-93	0.400		0.096					
11-Apr-93	0.000		0.236					
12-Apr-93	0.000		0.286					
13-Apr-93	0.000		0.289					
14-Apr-93	0.000		0.206					
15-Apr-93	0.080		0.241					
16-Apr-93	0.227		0.070					
17-Apr-93	0.000		0.053					
18-Apr-93	0.000		0.286					
19-Apr-93	1.267		0.081					
20-Apr-93	1.180		0.190					
21-Apr-93	0.000		0.221					
22-Apr-93	0.000		0.329					
23-Apr-93	0.000		0.358		12.418		24.331	
24-Apr-93	0.520		0.073					
25-Apr-93	0.900		0.075					
26-Apr-93	0.000		0.230					
27-Apr-93	0.020	1.440	0.302	1.038	12.982	-0.162	26.001	-1.268
28-Apr-93	0.000		0.167					
29-Apr-93	0.080		0.192					
30-Apr-93	0.260	1.780	0.330	1.728	12.719	-0.249	25.739	-1.355
1-May-93	0.000		0.396					
2-May-93	0.000		0.364					
3-May-93	0.000		0.335	2.723	10.760	0.715	23.085	0.304
4-May-93	0.360		0.080					
5-May-93	0.560	2.700	0.208	3.012	12.148	-0.042	26.144	-2.124
6-May-93	0.000		0.472					
7-May-93	0.000		0.447					
8-May-93	0.000		0.379					
9-May-93	0.000		0.495					
10-May-93	0.000		0.520					
11-May-93	0.000		0.399					
12-May-93	0.000		0.373					
13-May-93	0.000	2.700	0.293	6.389	11.033	-2.304	23.596	-2.954
14-May-93	0.600		0.211					
15-May-93	0.120		0.413					
16-May-93	0.000		0.393					
17-May-93	0.000	3.420	0.203	7.610	12.133	-3.905	25.009	-4.868
18-May-93	0.160		0.284					
19-May-93	0.220	3.800	0.130	8.024	12.703	-4.509	25.292	-5.185
20-May-93	0.020		0.256					
21-May-93	0.320	4.140	0.293	8.574	12.308	-4.324	25.457	-5.559
22-May-93	0.020		0.334					
23-May-93	0.060		0.113					
24-May-93	1.440		0.261					
25-May-93	0.060	5.720	0.117	9.398	15.010	6.270	28.580	-7.927
26-May-93	0.040		0.305					
27-May-93	0.380	6.140	0.304	10.006	14.183	-5.631	26.838	-6.373
28-May-93	0.000		0.197					
29-May-93	0.000		0.449					
30-May-93	0.000		0.422					
31-May-93	1.100		0.103					
1-Jun-93	0.100	7.340	0.291	11.468	15.110	-6.820	29.038	-8.835
2-Jun-93	0.020		0.414					
3-Jun-93	0.000	7.360	0.435	12.317	13.809	-6.348	26.658	-7.283
4-Jun-93	0.000		0.418					
5-Jun-93	0.340		0.083					
6-Jun-93	0.100		0.541					
7-Jun-93	0.280	8.080	0.317	13.677	13.955	-7.134	27.772	-9.037
8-Jun-93	0.500		0.086					
9-Jun-93	2.380	10.960	0.296	14.058	15.885	-6.565	29.374	-8.140
10-Jun-93	0.000		0.472					
11-Jun-93	0.000	10.960	0.490	15.020	15.681	-7.323	29.526	-9.254
12-Jun-93	0.000		0.495					
13-Jun-93	0.000		0.549					
14-Jun-93	0.460	11.420	0.450	16.514	13.207	-5.883	26.661	-7.424
15-Jun-93	0.000		0.449					
16-Jun-93	0.000	11.420	0.492	17.455	12.926	-6.543	26.129	-7.832
17-Jun-93	0.000		0.443					
18-Jun-93	0.560	11.980	0.297	18.194	12.761	-6.557	26.224	-8.107
19-Jun-93	1.300		0.100					
20-Jun-93	1.100		0.100					
21-Jun-93	3.580	19.960	0.218	18.612	17.457	-3.691	31.054	-5.375
22-Jun-93	0.020		0.525					
23-Jun-93	0.000	19.980	0.530	19.667	15.650	2.919	29.235	-4.591
24-Jun-93	0.000		0.542					
25-Jun-93	0.380	20.360	0.398	20.606	13.855	-1.683	27.305	-3.220
26-Jun-93	0.320		0.524					
27-Jun-93	0.140		0.311					
28-Jun-93	0.000	20.820	0.355	21.795	13.584	-2.141	27.470	-4.114
29-Jun-93	0.000		0.355					
30-Jun-93	0.000	20.820	0.257	22.407	12.759	-1.928	26.254	-3.511
1-Jul-93	0.000		0.461					
2-Jul-93	0.000	20.820	0.269	23.138	12.244	-2.144	25.712	-3.699
3-Jul-93	0.000		0.562					

## 1993 net drainage past the 40 cm and 80 cm depths (continued).

Date	Precipitation	Cum. Precipitation	AET	Cum. AET	Storage	Cum. Net	Storage	Cum. Net
	(cm)	(cm)	(cm)	(cm)	(40 cm)	Drainage (40 cm)	(80 cm)	Drainage (80 cm)
4-Jul-93	0.000		0.432					
5-Jul-93	0.000	20.820	0.581	24.713	11.032	-2.507	25.074	-4.636
6-Jul-93	1.140		0.266					
7-Jul-93	0.060	22.020	0.390	25.369	12.477	-3.408	25.631	-4.649
8-Jul-93	0.000		0.542					
9-Jul-93	3.020	25.040	0.500	26.411	12.077	-1.030	24.534	-1.574
10-Jul-93	0.020		0.517					
11-Jul-93	4.420		0.422					
12-Jul-93	0.000	29.480	0.531	27.882	16.216	-2.200	30.167	-4.237
13-Jul-93	0.000		0.481					
14-Jul-93	0.200	29.680	0.130	28.493	14.838	-1.233	28.864	-3.346
15-Jul-93	0.020		0.443					
16-Jul-93	0.000	29.700	0.530	29.466	14.536	-1.884	27.840	-3.275
17-Jul-93	0.000		0.502					
18-Jul-93	0.240		0.433					
19-Jul-93	1.360	31.300	0.163	30.563	15.431	-2.276	28.683	-3.615
20-Jul-93	0.020		0.474					
21-Jul-93	0.000	31.320	0.525	31.563	15.029	-2.854	29.317	-5.229
22-Jul-93	0.000		0.481					
23-Jul-93	0.000	31.320	0.536	32.580	13.599	-2.441	26.908	-3.836
24-Jul-93	0.000		0.501					
25-Jul-93	0.040		0.323					
26-Jul-93	1.460	32.820	0.415	33.819	15.869	-4.450	28.348	-5.016
27-Jul-93	0.000		0.366					
28-Jul-93	0.000	32.820	0.432	34.617	14.513	-3.892	27.937	-5.403
29-Jul-93	0.300		0.248					
30-Jul-93	0.020	33.140	0.131	34.996	14.199	-3.637	27.218	-4.742
31-Jul-93	0.000		0.540					
1-Aug-93	0.020		0.308					
2-Aug-93	0.000		0.330					
3-Aug-93	1.100	34.260	0.499	36.673	12.265	-2.260	24.599	-2.680
4-Aug-93	0.000		0.397					
5-Aug-93	0.020	34.280	0.416	37.486	13.225	-4.013	26.166	-5.041
6-Aug-93	0.060		0.436					
7-Aug-93	0.180		0.349					
8-Aug-93	0.020		0.359					
9-Aug-93	0.000	34.540	0.402	39.032	12.028	-4.102	24.250	-4.411
10-Aug-93	0.000		0.329					
11-Aug-93	0.220	34.760	0.341	39.702	12.567	-5.091	24.840	-5.451
12-Aug-93	0.000		0.488					
13-Aug-93	0.000	34.760	0.372	40.190	10.889	-4.272	23.751	-4.849
14-Aug-93	0.000	34.760	0.474	41.035				
15-Aug-93	0.000	34.960	0.294	41.330				
16-Aug-93	0.56	35.520	0.097	41.426	11.689	-5.177	23.678	-5.253
17-Aug-93	0	35.520	0.435	41.862				
18-Aug-93	0	35.520	0.474	42.336	10.714	-5.112	22.885	-5.370
19-Aug-93	0	35.520	0.392	42.628				
20-Aug-93	0.18	35.700	0.453	43.081	11.013	-5.976	22.812	-5.862
21-Aug-93	0	35.700	0.406	43.487				
22-Aug-93	0	35.700	0.408	43.895				
23-Aug-93	0.18	35.880	0.163	44.058	9.702	-5.462	20.732	-4.579
24-Aug-93	0.02	35.900	0.267	44.325				
25-Aug-93	0.02	35.920	0.452	44.777	9.740	-6.179	21.242	-5.768
26-Aug-93	0	35.920	0.327	45.104				
27-Aug-93	0.64	36.560	0.435	45.538	8.700	-5.260	19.977	-4.624
28-Aug-93	1.42	37.980	0.365	45.903				
29-Aug-93	0	37.980	0.176	46.079				
30-Aug-93	0	37.980	0.384	46.463	11.479	-7.544	22.846	-6.998
31-Aug-93	0	37.980	0.171	46.634				
1-Sep-93	0	37.980	0.376	47.010	10.952	-7.564	22.770	-7.468
2-Sep-93	2.18	40.160	0.148	47.157				
3-Sep-93	0	40.160	0.086	47.244	13.787	-8.453	25.413	-8.165
4-Sep-93	1.07	41.230	0.399	47.542				
5-Sep-93	0	41.230	0.305	47.847				
6-Sep-93	0	41.230	0.122	47.969				
7-Sep-93	0.48	41.710	0.284	48.253				
8-Sep-93	0.02	41.730	0.241	48.493	13.536	-7.881	25.341	-7.773
9-Sep-93	0.28	42.010	0.182	48.675				
10-Sep-93	1.5	43.510	0.107	48.782				
11-Sep-93	0.45	43.960	0.129	48.911				
12-Sep-93	0.02	43.980	0.119	49.030				
13-Sep-93	0	43.980	0.338	49.368				
14-Sep-93	0.08	44.060	0.270	49.638				
15-Sep-93	1.16	45.220	0.123	49.761	15.478	-7.601	28.214	-8.424
16-Sep-93	0	45.220	0.278	50.039				
17-Sep-93	0	45.220	0.145	50.183	14.234	-6.779	26.019	-6.651
18-Sep-93	0	45.220	0.118	50.301				
19-Sep-93	0.02	45.240	0.268	50.569				
20-Sep-93	0.02	45.260	0.076	50.646				
21-Sep-93	0.18	45.440	0.113	50.759				
22-Sep-93	0.02	45.460	0.229	50.988	12.778	-5.888	22.901	-4.098
23-Sep-93	0.08	45.540	0.194	51.182				
24-Sep-93	0.02	45.560	0.224	51.405				
25-Sep-93	0.2	45.760	0.192	51.597				
26-Sep-93	0.38	46.140	0.036	51.633				
27-Sep-93	0.48	46.620	0.402	51.662				
28-Sep-93	0.9	47.520	0.063	51.725				
29-Sep-93	0.08	47.600	0.109	51.834				
30-Sep-93	0.04	47.640	0.164	51.998				

## 1993 net drainage past the 40 cm and 80 cm depths (continued).

Date	Precipitation	Cum. Precipitation	AET	Cum. AET	Storage	Cum. Net	Storage	Cum. Net
	(cm)	(cm)	(cm)	(cm)	(40 cm)	Drainage (40 cm)	(80 cm)	Drainage (80 cm)
1-Oct-93	0.76	48 400	0.083	52 082	14 306	-5 570	25 498	-4 848
2-Oct-93	0.2	48 600	0.141	52 223				
3-Oct-93	0.02	48 620	0.175	52 398				
4-Oct-93	0.1	48 720	0.059	52 457				
5-Oct-93	0.02	48 740	0.153	52 591				
6-Oct-93	0.02	48 760	0.109	52 700				
7-Oct-93	0	48 760	0.230	52 930				
8-Oct-93	0.02	48 780	0.235	53 165				
9-Oct-93	1.3	50 080	0.092	53 257				
10-Oct-93	0	50 080	0.130	53 387				
11-Oct-93	0.02	50 100	0.218	53 605				
12-Oct-93	0.04	50 140	0.039	53 644				
13-Oct-93	0	50 140	0.121	53 766				
14-Oct-93	0.02	50 160	0.140	53 905	14 633	-5 960	26 4	-5 814
15-Oct-93	0	50 160	0.061	53 966				
16-Oct-93	0.86	51 020	0.045	54 011				
17-Oct-93	1.92	52 940	0.022	54 034				
18-Oct-93	0.02	52 940	0.102	54 135	15 598	-4 375	28 48	-5 344
19-Oct-93	0.02	52 960	0.072	54 207				
20-Oct-93	0.46	53 420	0.074	54 281				
21-Oct-93	0.84	54 260	0.115	54 396	15 393	-3 130	28 48	-4 304
22-Oct-93	0.02	54 280	0.039	54 435				
23-Oct-93	0.04	54 320	0.141	54 577				
24-Oct-93	0	54 320	0.152	54 729				
25-Oct-93	0	54 320	0.131	54 860				
26-Oct-93	0.04	54 320	0.135	54 995	14 558	-2 815	27 28	-3 624
27-Oct-93	0.04	54 360	0.039	55 034				
28-Oct-93	0.02	54 380	0.058	55 092	14 476	-2 770	27 2	-3 581
29-Oct-93	0	54 380	0.050	55 142				
30-Oct-93	0.16	54 540	0.048	55 190				
31-Oct-93	0.18	54 720	0.033	55 223				
1-Nov-93	0.02	54 740	0.000	55 223				
2-Nov-93	0	54 740	0.000	55 223				
3-Nov-93	0.22	54 960	0.000	55 223				
4-Nov-93	0.12	55 080	0.000	55 223				
5-Nov-93	0.52	55 600	0.000	55 223				
6-Nov-93	0	55 600	0.000	55 223				
7-Nov-93	0.02	55 620	0.000	55 223				
8-Nov-93	0	55 620	0.000	55 223	14 925	-2 110	27 2	-2 472
9-Nov-93	0	55 620	0.000	55 223				
10-Nov-93	0.04	55 660	0.000	55 223				
11-Nov-93	0.06	55 720	0.000	55 223				
12-Nov-93	0	55 720	0.000	55 223	14 52	-1 605	27 9	-3 072
13-Nov-93	0.3	56 020	0.000	55 223				
14-Nov-93	0.26	56 280	0.000	55 223				
15-Nov-93	0.3	56 580	0.000	55 223				
16-Nov-93	0	56 580	0.000	55 223				
17-Nov-93	0.12	56 700	0.000	55 223				
18-Nov-93	0.02	56 720	0.000	55 223				
19-Nov-93	0.3	57 020	0.000	55 223				
20-Nov-93	0	57 020	0.000	55 223				
21-Nov-93	0	57 020	0.000	55 223				
22-Nov-93	0	57 020	0.000	55 223				
23-Nov-93	0	57 020	0.000	55 223				
24-Nov-93	0.2	57 220	0.000	55 223				
25-Nov-93	0	57 220	0.000	55 223				
26-Nov-93	0.26	57 480	0.000	55 223				
27-Nov-93	2.56	60 040	0.000	55 223				
28-Nov-93	0.26	60 300	0.000	55 223				
29-Nov-93	0	60 300	0.000	55 223				
30-Nov-93	0.06	60 360	0.000	55 223				
1-Dec-93	0.02	60 380	0.000	55 223				
2-Dec-93	0.4	60 780	0.000	55 223	16 683	1 392	29 4	0 488
3-Dec-93	0.02	60 800	0.000	55 223				
4-Dec-93	0.36	61 160	0.000	55 223				
5-Dec-93	0	61 160	0.000	55 223				
6-Dec-93	0.46	61 620	0.000	55 223	15 501	3 314	30 3	0 428
7-Dec-93	0	61 620	0.000	55 223				
8-Dec-93	0	61 620	0.000	55 223				
9-Dec-93	0	61 620	0.000	55 223				
10-Dec-93	0.32	61 940	0.000	55 223				
11-Dec-93	0	61 940	0.000	55 223				
12-Dec-93	0.02	61 960	0.000	55 223				
13-Dec-93	0	61 960	0.000	55 223				
14-Dec-93	0	61 960	0.000	55 223	15 3	3 855	30 2	0 868

Appendix 5: 1991, 1992 and 1993 Grain and Stover Yields, Grain and Stover N Concentrations.

# 1991 Grain Yield, Grain N Concentration, Stover Yield and Stover N Concentration\*

N Source	Appl. Time	Appl. Rate	Block	Grain Yield (t ha <sup>-1</sup> )	Grain N Conc (%)	Stover Yield (t ha <sup>-1</sup> )	Stover N Conc (%)
Fert	Spring	L	1	9.71	1.52		
Fert	Spring	M	1	9.62	1.56		
Fert	Spring	H	1	10.03	1.56		
LCM	Spring	L	1	10.39	1.39		
LCM	Spring	M	1	9.68	1.50		
LCM	Spring	H	1	9.44	1.47		
SBM	Spring	L	1	9.63	1.43		
SBM	Spring	M	1	8.99	1.33		
SBM	Spring	H	1	9.43	1.40		
Fert	Fall	L	1				
Fert	Fall	M	1				
Fert	Fall	H	1				
LCM	Fall	L	1				
LCM	Fall	M	1				
LCM	Fall	H	1				
SBM	Fall	L	1				
SBM	Fall	M	1				
SBM	Fall	H	1				
Check	Check	Check	1	10.10	1.41		
Fert	Spring	L	2	9.45	1.43		
Fert	Spring	M	2	9.46	1.45		
Fert	Spring	H	2	10.05	1.57		
LCM	Spring	L	2	8.24	1.16		
LCM	Spring	M	2	8.92	1.33		
LCM	Spring	H	2	10.12	1.16		
SBM	Spring	L	2	6.41	1.39		
SBM	Spring	M	2	8.29	0.96		
SBM	Spring	H	2	7.51	1.23		
Fert	Fall	L	2				
Fert	Fall	M	2				
Fert	Fall	H	2				
LCM	Fall	L	2				
LCM	Fall	M	2				
LCM	Fall	H	2				
SBM	Fall	L	2				
SBM	Fall	M	2				
SBM	Fall	H	2				
Check	Check	Check	2	7.09	1.01		
Fert	Spring	L	3	10.18	1.53		
Fert	Spring	M	3	9.13	1.52		
Fert	Spring	H	3	9.40	1.44		
LCM	Spring	L	3	8.97	1.41		
LCM	Spring	M	3	9.53	1.35		
LCM	Spring	H	3	9.39	1.46		
SBM	Spring	L	3	8.63	1.30		
SBM	Spring	M	3	8.85	1.35		
SBM	Spring	H	3	7.99	1.16		
Fert	Fall	L	3				
Fert	Fall	M	3				
Fert	Fall	H	3				
LCM	Fall	L	3				
LCM	Fall	M	3				
LCM	Fall	H	3				
SBM	Fall	L	3				
SBM	Fall	M	3				
SBM	Fall	H	3				
Check	Check	Check	3	8.37	1.27		
Fert	Spring	L	4	9.36	1.55		
Fert	Spring	M	4	9.16	1.53		
Fert	Spring	H	4	9.29	1.64		
LCM	Spring	L	4	8.85	1.41		
LCM	Spring	M	4	9.26	1.54		
LCM	Spring	H	4	9.58	1.46		
SBM	Spring	L	4	6.79	1.12		
SBM	Spring	M	4	8.76	1.30		
SBM	Spring	H	4	7.44	1.51		
Fert	Fall	L	4				
Fert	Fall	M	4				
Fert	Fall	H	4				
LCM	Fall	L	4				
LCM	Fall	M	4				
LCM	Fall	H	4				
SBM	Fall	L	4				
SBM	Fall	M	4				
SBM	Fall	H	4				
Check	Check	Check	4	9.12	1.56		

\* Fert, LCM, SBM, Check - Fertilizer, Liquid Cattle Manure, Solid Beef Manure and Control plots, respectively. H, M, L - High, Medium and Low rates of application, respectively.

# 1992 Grain Yield, Grain N Concentration, Stover Yield and Stover N Concentration\*

N Source	Appl Time	Appl Rate	Block	Grain Yield (t ha <sup>-1</sup> )	Grain N Conc. (%)	Stover Yield (t ha <sup>-1</sup> )	Stover N Conc. (%)
Fert	Spring	L	1	536	1.15	2699	0.65
Fert	Spring	M	1	691	1.30	3629	0.72
Fert	Spring	H	1	577	1.34	3484	0.68
LCM	Spring	L	1	625	1.16	2854	0.5
LCM	Spring	M	1	620	1.39	3223	0.65
LCM	Spring	H	1	623	1.43	2669	0.65
SBM	Spring	L	1	585	1.27	2891	0.43
SBM	Spring	M	1	694	1.25	3378	0.57
SBM	Spring	H	1	683	1.30	2701	0.59
Fert	Fall	L	1	571	1.07	2592	0.39
Fert	Fall	M	1	538	1.20	2710	0.54
Fert	Fall	H	1	586	1.13	3346	0.59
LCM	Fall	L	1	526	1.04	2457	0.48
LCM	Fall	M	1	567	1.10	2335	0.51
LCM	Fall	H	1	608	1.23	2576	0.53
SBM	Fall	L	1	539	0.85	2436	0.37
SBM	Fall	M	1	613	1.21	2794	0.48
SBM	Fall	H	1	643	1.28	3215	0.79
Check	Check	Check	1	428	0.91	2137	0.38
Fert	Spring	L	2	468	1.15	2665	0.56
Fert	Spring	M	2	564	1.29	2579	0.7
Fert	Spring	H	2	475	1.38	2131	0.74
LCM	Spring	L	2	624	1.21	2719	0.44
LCM	Spring	M	2	573	1.23	2521	0.5
LCM	Spring	H	2	578	1.32	3063	0.58
SBM	Spring	L	2	480	1.08	2253	0.29
SBM	Spring	M	2	665	1.24	2971	0.37
SBM	Spring	H	2	645	1.25	2690	0.57
Fert	Fall	L	2	426	1.11	1961	0.41
Fert	Fall	M	2	515	1.30	2472	0.59
Fert	Fall	H	2	431	1.22	2385	0.49
LCM	Fall	L	2	396	0.93	1811	0.37
LCM	Fall	M	2	493	0.96	2676	0.55
LCM	Fall	H	2	548	1.09	2644	0.62
SBM	Fall	L	2	543	1.17	1959	0.4
SBM	Fall	M	2	472	1.04	2175	0.37
SBM	Fall	H	2	573	1.21	2886	0.57
Check	Check	Check	2	323	0.70	1782	0.25
Fert	Spring	L	3	495	1.42	2353	0.46
Fert	Spring	M	3	522	1.32	2958	0.72
Fert	Spring	H	3	540	1.39	2719	0.67
LCM	Spring	L	3	668	1.25	3300	0.78
LCM	Spring	M	3	633	1.17	3855	0.45
LCM	Spring	H	3	567	1.36	2619	0.54
SBM	Spring	L	3	463	1.30	2540	0.41
SBM	Spring	M	3	660	1.35	3512	0.67
SBM	Spring	H	3	672	1.36	3689	0.64
Fert	Fall	L	3	426	1.13	2455	0.46
Fert	Fall	M	3	371	1.16	2045	0.35
Fert	Fall	H	3	394	1.06	2166	0.33
LCM	Fall	L	3	402	1.05	1956	0.39
LCM	Fall	M	3	542	1.18	2109	0.46
LCM	Fall	H	3	392	1.03	1846	0.52
SBM	Fall	L	3	424	1.09	2517	0.39
SBM	Fall	M	3	507	1.29	2860	0.49
SBM	Fall	H	3	595	1.24	3200	0.48
Check	Check	Check	3	408	1.02	2730	0.23
Fert	Spring	L	4	569	1.23	2879	0.54
Fert	Spring	M	4	576	1.51	2703	0.73
Fert	Spring	H	4	516	1.44	2733	0.65
LCM	Spring	L	4	527	1.33	2548	0.59
LCM	Spring	M	4	588	1.32	2738	0.54
LCM	Spring	H	4	732	1.45	3538	0.64
SBM	Spring	L	4	573	1.22	2351	0.41
SBM	Spring	M	4	701	1.37	3024	0.5
SBM	Spring	H	4	706	1.40	3423	0.57
Fert	Fall	L	4	364	1.05	1580	0.53
Fert	Fall	M	4	533	1.21	2971	0.54
LCM	Fall	L	4	406	1.17	2515	0.34
LCM	Fall	M	4	557	1.06	2036	0.62
LCM	Fall	H	4	464	1.20	2209	0.48
SBM	Fall	L	4	439	1.21	2426	0.48
SBM	Fall	M	4	595	1.21	2107	0.64
SBM	Fall	H	4	682	1.36	2829	0.51
Check	Check	Check	4	371	1.29	1589	0.37

\* Fert, LCM, SBM, Check - Fertilizer, Liquid Cattle Manure, Solid Beef Manure and Control plots, respectively. H, M, L - High, Medium and Low rates of application, respectively.

# 1993 Grain Yield, Grain N Concentration, Stover Yield and Stover N Concentration \*

N Source	Appl. Time	Appl. Rate	Block	Grain Yield	Grain N Conc.	Stover Yield	Stover N Conc
				(t ha <sup>-1</sup> )	(%)	(t ha <sup>-1</sup> )	(%)
Fert	Spring	L	1	6 910	1 260	4 950	530
Fert	Spring	M	1	6 890	1 400	5 812	920
Fert	Spring	H	1	6 690	1 420	4 896	670
LCM	Spring	L	1	7 010	1 170	6 414	600
LCM	Spring	M	1	6 140	1 320	5 227	600
LCM	Spring	H	1	6 460	1 260	4 156	670
SBM	Spring	L	1	6 640	1 080	4 107	840
SBM	Spring	M	1	7 060	1 130	5 154	750
SBM	Spring	H	1	6 070	1 280	4 173	620
Fert	Fall	L	1	5 530	1 090	4 183	580
Fert	Fall	M	1	7 330	1 270	5 516	670
Fert	Fall	H	1	6 030	1 130	4 270	580
LCM	Fall	L	1	6 740	1 020	4 980	600
LCM	Fall	M	1	6 540	1 130	4 995	600
LCM	Fall	H	1	6 720	1 390	4 995	700
SBM	Fall	L	1	5 530	970	3 056	430
SBM	Fall	M	1	6 340	1 270	4 362	620
SBM	Fall	H	1	6 910	1 170	4 415	580
Check	Check	Check	1	4 610	970	3 663	510
Fert	Spring	L	2	5 370	1 370	4 122	630
Fert	Spring	M	2	6 880	1 410	5 245	780
Fert	Spring	H	2	7 130	1 420	5 152	710
LCM	Spring	L	2	6 850	1 260	4 905	560
LCM	Spring	M	2	6 060	1 380	4 888	530
LCM	Spring	H	2	8 060	1 460	7 017	430
SBM	Spring	L	2	5 470	1 150	3 600	520
SBM	Spring	M	2	6 080	1 500	4 984	420
SBM	Spring	H	2	7 610	1 430	5 661	670
Fert	Fall	L	2	4 760	1 160	3 964	390
Fert	Fall	M	2	6 070	1 250	4 045	560
Fert	Fall	H	2	6 870	1 290	6 312	660
LCM	Fall	L	2	6 440	1 110	5 052	510
LCM	Fall	M	2	6 290	1 110	4 515	520
LCM	Fall	H	2	6 220	1 300	5 287	460
SBM	Fall	L	2	5 400	970	3 712	480
SBM	Fall	M	2	5 460	1 100	3 513	580
SBM	Fall	H	2	7 930	1 360	6 442	510
Check	Check	Check	2	3 740	940	3 124	470
Fert	Spring	L	3	6 555	1 430	4 891	580
Fert	Spring	M	3	7 181	1 530	6 346	760
Fert	Spring	H	3	6 329	1 610	4 787	750
LCM	Spring	L	3	5 899	1 460	3 878	680
LCM	Spring	M	3	6 073	1 260	5 305	580
LCM	Spring	H	3	6 292	1 460	5 177	640
SBM	Spring	L	3	5 366	1 340	3 482	610
SBM	Spring	M	3	7 240	1 510	5 251	480
SBM	Spring	H	3	7 140	1 490	3 695	590
Fert	Fall	L	3	5 800	1 200	4 233	530
Fert	Fall	M	3	5 710	1 420	4 294	610
Fert	Fall	H	3	5 720	1 540	4 201	580
LCM	Fall	L	3	4 630	1 220	2 848	490
LCM	Fall	M	3	6 620	1 460	5 151	670
LCM	Fall	H	3	5 480	1 450	3 553	690
SBM	Fall	L	3	5 520	1 160	1 528	590
SBM	Fall	M	3	5 870	1 540	4 157	720
SBM	Fall	H	3	6 930	1 440	4 838	680
Check	Check	Check	3	2 530	1 050	1 714	340
Fert	Spring	L	4	6 310	1 170	5 070	570
Fert	Spring	M	4	6 860	1 380	5 293	490
Fert	Spring	H	4	6 120	1 510	6 417	840
LCM	Spring	L	4	5 860	1 460	4 266	620
LCM	Spring	M	4	5 899	1 560	4 159	400
LCM	Spring	H	4	6 300	1 470	4 818	780
SBM	Spring	L	4	6 430	1 280	4 866	470
SBM	Spring	M	4	6 080	1 230	5 502	500
SBM	Spring	H	4	6 880	1 560	4 554	700
Fert	Fall	L	4	5 090	1 160	4 307	650
Fert	Fall	M	4	5 920	1 370	4 578	580
Fert	Fall	H	4	5 350	1 310	4 062	660
LCM	Fall	L	4	4 570	1 040	3 516	440
LCM	Fall	M	4	6 080	1 220	4 200	550
LCM	Fall	H	4	5 180	1 360	3 812	760
SBM	Fall	L	4	3 870	1 230	2 390	720
SBM	Fall	M	4	6 200	1 340	4 804	450
SBM	Fall	H	4	6 270	1 540	3 650	620
Check	Check	Check	4	3 710	820	3 096	460

\* Fert, LCM, SBM, Check - Fertilizer, Liquid Cattle Manure, Solid Beef Manure and Control plots, respectively.  
H, M, L - High, Medium and Low rates of application, respectively.

Appendix 6: 1993 Leaf Area Index, Crop Height and Number of Leaves.



1993 Leaf Area Index (LAI), Crop Height and Number of Leaves.

Date	Days After Emergence (days)	LAI	Crop Height (cm)	# of Leaves
June 7, 1993	0	0	0	0
June 9, 1993	2	0.05	6	3
June 14, 1993	7	0.10	8.2	3
June 23, 1993	16	0.16	20.4	4
July 2, 1993	25	0.25	39	5
July 6, 1993	29	0.79	58	7
July 9, 1993	32	0.98	77.8	7
July 12, 1993	35	1.83	98	8
July 14, 1993	37		105.2	8
July 23, 1993	46		169.4	9
July 26, 1993	49	2.64	241.4	11
July 30, 1993	53	3.48	246.4	11
August 3, 1993	57	3.10	247.2	12
August 9, 1993	63	3.08	254.8	12
August 16, 1993	70	3.51	279.0	12
August 23, 1993	77	3.82	287.8	13
August 30, 1993	84	3.69	284.0	13

Planting - May 13, 1993

100% Emergence - June 7, 1993

Appendix 7: 1992 and 1993  $\text{Cl}^-$  Tracer Experiments.

1992 subplot experiment amounts of  $\text{Cl}^-$  from the 0 - 1 m depth at two dates.

Date	Depth (cm)	$\text{Cl}^-$ (mg kg <sup>-1</sup> )
4-Jun-92	5	516.67
4-Jun-92	15	76.97
4-Jun-92	25	14.94
4-Jun-92	35	26.04
4-Jun-92	45	38.77
4-Jun-92	55	24.46
4-Jun-92	65	52.16
4-Jun-92	75	62.35
4-Jun-92	85	39.93
4-Jun-92	95	29.46
10-Aug-92	5	49.87
10-Aug-92	15	220.19
10-Aug-92	25	139.57
10-Aug-92	35	54.60
10-Aug-92	45	26.16
10-Aug-92	55	11.19
10-Aug-92	65	10.97
10-Aug-92	75	9.46
10-Aug-92	85	8.98
10-Aug-92	95	7.98

$\text{Cl}^-$  Applied May 19, 1992.

1993 subplot experiment distribution of  $\text{Cl}^-$  from the 0 - 1 m depth at seven sampling dates.

Date	Depth (cm)	$\text{Cl}^-$ (mg kg <sup>-1</sup> )
April 23, 1993	5	57.85
April 23, 1993	15	55.82
April 23, 1993	25	43.27
April 23, 1993	35	47.83
April 23, 1993	45	37.81
April 23, 1993	55	31.54
April 23, 1993	65	20.14
April 23, 1993	75	18.01
April 23, 1993	85	12.17
April 23, 1993	95	10.65
May 7, 1993	5	60.69
May 7, 1993	15	53.31
May 7, 1993	25	49.55
May 7, 1993	35	44.33
May 7, 1993	45	37.34
May 7, 1993	55	30.48
May 7, 1993	65	20.80
May 7, 1993	75	19.51
May 7, 1993	85	10.01
May 7, 1993	95	10.45
June 2, 1993	5	68.69
June 2, 1993	15	58.86
June 2, 1993	25	43.76
June 2, 1993	35	44.73
June 2, 1993	45	31.23
June 2, 1993	55	19.61
June 2, 1993	65	13.89
June 2, 1993	75	8.31
June 2, 1993	85	8.47
June 2, 1993	95	1.12
June 28, 1993	5	42.12
June 28, 1993	15	40.93
June 28, 1993	25	39.72
June 28, 1993	35	33.37
June 28, 1993	45	26.05
June 28, 1993	55	18.43
June 28, 1993	65	16.57
June 28, 1993	75	9.09
June 28, 1993	85	11.70
June 28, 1993	95	7.61
July 23, 1993	5	4.73
July 23, 1993	15	9.77
July 23, 1993	25	11.01
July 23, 1993	35	15.10
July 23, 1993	45	8.11
July 23, 1993	55	5.01
July 23, 1993	65	1.44
July 23, 1993	75	0.00
July 23, 1993	85	0.55
July 23, 1993	95	1.24
August 18, 1993	5	6.24
August 18, 1993	15	19.83
August 18, 1993	25	19.46
August 18, 1993	35	14.19
August 18, 1993	45	9.06
August 18, 1993	55	4.64
August 18, 1993	65	2.19
August 18, 1993	75	2.33
August 18, 1993	85	0.93
August 18, 1993	95	0.00
1-Sep-93	5	14.72
1-Sep-93	15	14.52
1-Sep-93	25	12.31
1-Sep-93	35	6.25
1-Sep-93	45	0.00
1-Sep-93	55	0.00
1-Sep-93	65	0.00
1-Sep-93	75	0.00
1-Sep-93	85	0.00
1-Sep-93	95	0.00

$\text{Cl}^-$  Applied December 8, 1992

1993 detailed experiment distribution of  $\text{Cl}^-$  from the 0 - .8 m depth at seven sampling dates.

Date	Depth (cm)	$\text{Cl}^-$ (mg kg <sup>-1</sup> )	Date	Depth (cm)	$\text{Cl}^-$ (mg kg <sup>-1</sup> )
23-Jun-93	2.5	85.77	25-Nov-93	2.5	8.28
23-Jun-93	7.5	291.87	25-Nov-93	7.5	20.47
23-Jun-93	12.5	320.95	25-Nov-93	12.5	25.78
23-Jun-93	17.5	195.69	25-Nov-93	17.5	45.48
23-Jun-93	22.5	114.24	25-Nov-93	22.5	88.78
23-Jun-93	27.5	50.28	25-Nov-93	27.5	57.22
23-Jun-93	32.5	36.29	25-Nov-93	32.5	113.01
23-Jun-93	37.5	18.60	25-Nov-93	37.5	66.87
23-Jun-93	42.5	14.21	25-Nov-93	42.5	89.50
23-Jun-93	47.5	6.58	25-Nov-93	47.5	74.58
23-Jun-93	52.5	0	25-Nov-93	52.5	63.59
23-Jun-93	57.5	0	25-Nov-93	57.5	49.61
23-Jun-93	62.5	0	25-Nov-93	62.5	49.48
23-Jun-93	67.5	0	25-Nov-93	67.5	25.45
23-Jun-93	72.5	0	25-Nov-93	72.5	16.59
23-Jun-93	77.5	0	25-Nov-93	77.5	11.35
15-Jul-93	2.5	105.59	14-Dec-94	2.5	6.68
15-Jul-93	7.5	309.67	14-Dec-94	7.5	14.96
15-Jul-93	12.5	263.62	14-Dec-94	12.5	37.44
15-Jul-93	17.5	189.71	14-Dec-94	17.5	34.28
15-Jul-93	22.5	72.07	14-Dec-94	22.5	49.09
15-Jul-93	27.5	31.02	14-Dec-94	27.5	33.23
15-Jul-93	32.5	12.23	14-Dec-94	32.5	80.39
15-Jul-93	37.5	8.90	14-Dec-94	37.5	75.23
15-Jul-93	42.5	11.65	14-Dec-94	42.5	77.08
15-Jul-93	47.5	11.40	14-Dec-94	47.5	68.76
15-Jul-93	52.5	6.22	14-Dec-94	52.5	51.47
15-Jul-93	57.5	6.12	14-Dec-94	57.5	37.05
15-Jul-93	62.5	4.12	14-Dec-94	62.5	32.38
15-Jul-93	67.5	0	14-Dec-94	67.5	31.69
15-Jul-93	72.5	0	14-Dec-94	72.5	32.19
15-Jul-93	77.5	0	14-Dec-94	77.5	21.55
9-Aug-93	2.5	117.46			
9-Aug-93	7.5	178.98			
9-Aug-93	12.5	263.62			
9-Aug-93	17.5	304.01			
9-Aug-93	22.5	173.41			
9-Aug-93	27.5	127.64			
9-Aug-93	32.5	76.91			
9-Aug-93	37.5	52.91			
9-Aug-93	42.5	46.88			
9-Aug-93	47.5	14.65			
9-Aug-93	52.5	12.34			
9-Aug-93	57.5	14.42			
9-Aug-93	62.5	15.10			
9-Aug-93	67.5	6.89			
9-Aug-93	72.5	5.52			
9-Aug-93	77.5	0			
1-Sep-93	2.5	100.98			
1-Sep-93	7.5	197.34			
1-Sep-93	12.5	293.20			
1-Sep-93	17.5	279.36			
1-Sep-93	22.5	204.55			
1-Sep-93	27.5	132.26			
1-Sep-93	32.5	57.67			
1-Sep-93	37.5	37.07			
1-Sep-93	42.5	33.12			
1-Sep-93	47.5	7.54			
1-Sep-93	52.5	6.27			
1-Sep-93	57.5	4.53			
1-Sep-93	62.5	7.26			
1-Sep-93	67.5	3.19			
1-Sep-93	72.5	0.00			
1-Sep-93	77.5	0.00			
26-Oct-93	2.5	104.49			
26-Oct-93	7.5	104.33			
26-Oct-93	12.5	121.34			
26-Oct-93	17.5	171.53			
26-Oct-93	22.5	153.74			
26-Oct-93	27.5	169.50			
26-Oct-93	32.5	178.05			
26-Oct-93	37.5	171.32			
26-Oct-93	42.5	178.57			
26-Oct-93	47.5	123.63			
26-Oct-93	52.5	68.19			
26-Oct-93	57.5	19.22			
26-Oct-93	62.5	15.14			
26-Oct-93	67.5	10.42			
26-Oct-93	72.5	8.17			
26-Oct-93	77.5	5.37			

$\text{Cl}^-$  Applied June 2, 1993.

Appendix 8: Computer Data File Names and Contents.

List of computer data files and their contents<sup>1</sup>.

File Name	File Contents
Soln91.txt	1991 soil solution samples
Soln92.txt	1992 soil solution samples
Soln93.txt	1993 soil solution samples
SoilN91.txt	1991 Mineral N, Extractable N and Extractable C samples
SoilN92.txt	1992 Mineral N, Extractable N and Extractable C samples
SoilN93.txt	1993 Mineral N, Extractable N and Extractable C samples
TDR9192.txt	1991 and 1992 Individual soil water content measurements
TDR93.txt	1993 Individual soil water content measurements

## Appendix 9: Mathcad Program for Detailed $\text{Cl}^-$ Experiment Analyses.



ORIGIN := 1

M := READPRN(DetKCL93txt)

M =

2.5	85.77	105.59	117.46	100.98	104.49	8.28	6.68	1.25
7.5	291.87	309.67	178.98	197.34	104.33	20.47	14.96	1.25
12.5	320.95	263.62	263.62	293.2	121.34	25.78	37.44	1.25
17.5	195.69	189.71	304.01	279.36	171.53	45.48	34.28	1.3
22.5	114.24	72.07	173.41	204.55	153.74	88.78	49.09	1.3
27.5	50.28	31.02	127.64	132.26	169.5	57.22	33.23	1.54
32.5	36.29	12.23	76.91	57.67	178.05	113.01	80.39	1.54
37.5	18.6	8.9	52.91	37.07	171.32	66.87	75.23	1.54
42.5	14.21	11.65	46.88	33.12	178.57	89.5	77.08	1.59
47.5	6.58	11.4	14.65	7.54	123.63	74.58	68.76	1.59
52.5	0	6.22	12.34	6.27	68.19	63.59	51.47	1.72
57.5	0	6.12	14.42	4.53	19.22	49.61	37.05	1.76
62.5	0	4	15.1	7.26	15	49.48	32.38	1.87
67.5	0	0	6.89	3.19	10	25.45	31.69	1.92
72.5	0	0	5.52	0	8	16.59	32.19	1.92
77.5	0	0	0	0	5	11.35	21.55	1.95

m := length(M<sup><1></sup>)

D := M<sup><1></sup>

m = 16

i := 1..m

n := cols(M)

n = 9

j := 2..n - 1

BulkDens<sub>i</sub> := (M<sup><n></sup>)<sub>i</sub>

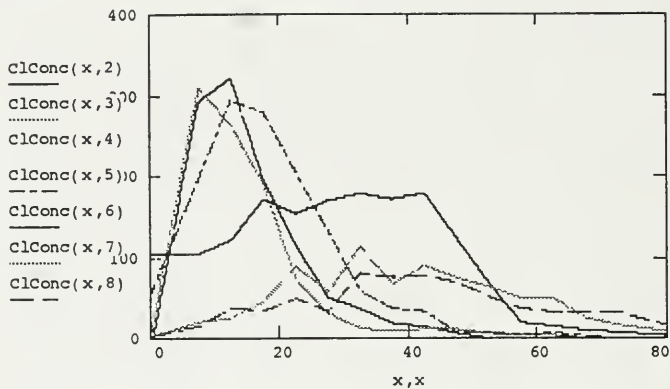
x := 0,.1..80

k := 1..801

ClConc(x,j) := linterp(D,M<sup><j></sup>,x)

Depth<sub>k</sub> := (k - 1) \* .1

$\text{ClConc}(x, j) := \text{if}(\text{ClConc}(x, j) < 0, 0, \text{ClConc}(x, j))$



$$\text{Area}_{(1,j)} := \int_0^5 \text{ClConc}(x, j) \, dx$$

$$\text{Area}_{(2,j)} := \int_5^{10} \text{ClConc}(x, j) \, dx$$

$$\text{Area}_{(3,j)} := \int_{10}^{15} \text{ClConc}(x, j) \, dx$$

$$\text{Area}_{(4,j)} := \int_{15}^{20} \text{ClConc}(x, j) \, dx$$

$$\text{Area}_{(5,j)} := \int_{20}^{25} \text{ClConc}(x, j) \, dx$$

$$\text{Area}_{(6,j)} := \int_{25}^{30} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(7,j)} := \int_{30}^{35} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(8,j)} := \int_{35}^{40} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(9,j)} := \int_{40}^{45} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(10,j)} := \int_{45}^{50} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(11,j)} := \int_{50}^{55} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(12,j)} := \int_{55}^{60} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(13,j)} := \int_{60}^{65} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(14,j)} := \int_{65}^{70} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(15,j)} := \int_{70}^{75} \text{ClConc}(x,j) \, dx$$

$$\text{Area}_{(16,j)} := \int_{75}^{80} \text{ClConc}(x,j) \, dx$$

$$\text{MPA}_{(i,j)} := \frac{\text{Area}_{(i,j)}}{1000000} \cdot \text{BulkDens}_i \cdot 10000$$

$$i := 1 \dots 16$$

$$\text{TotalMPA}_j := \sum_i \text{MPA}_{(i,j)}$$

$$\text{TotalMPA} = \begin{bmatrix} 0 \\ 72.13505 \\ 65.23758 \\ 95.2673 \\ 90.42057 \\ 116.91455 \\ 62.93537 \\ 54.04815 \end{bmatrix}$$



